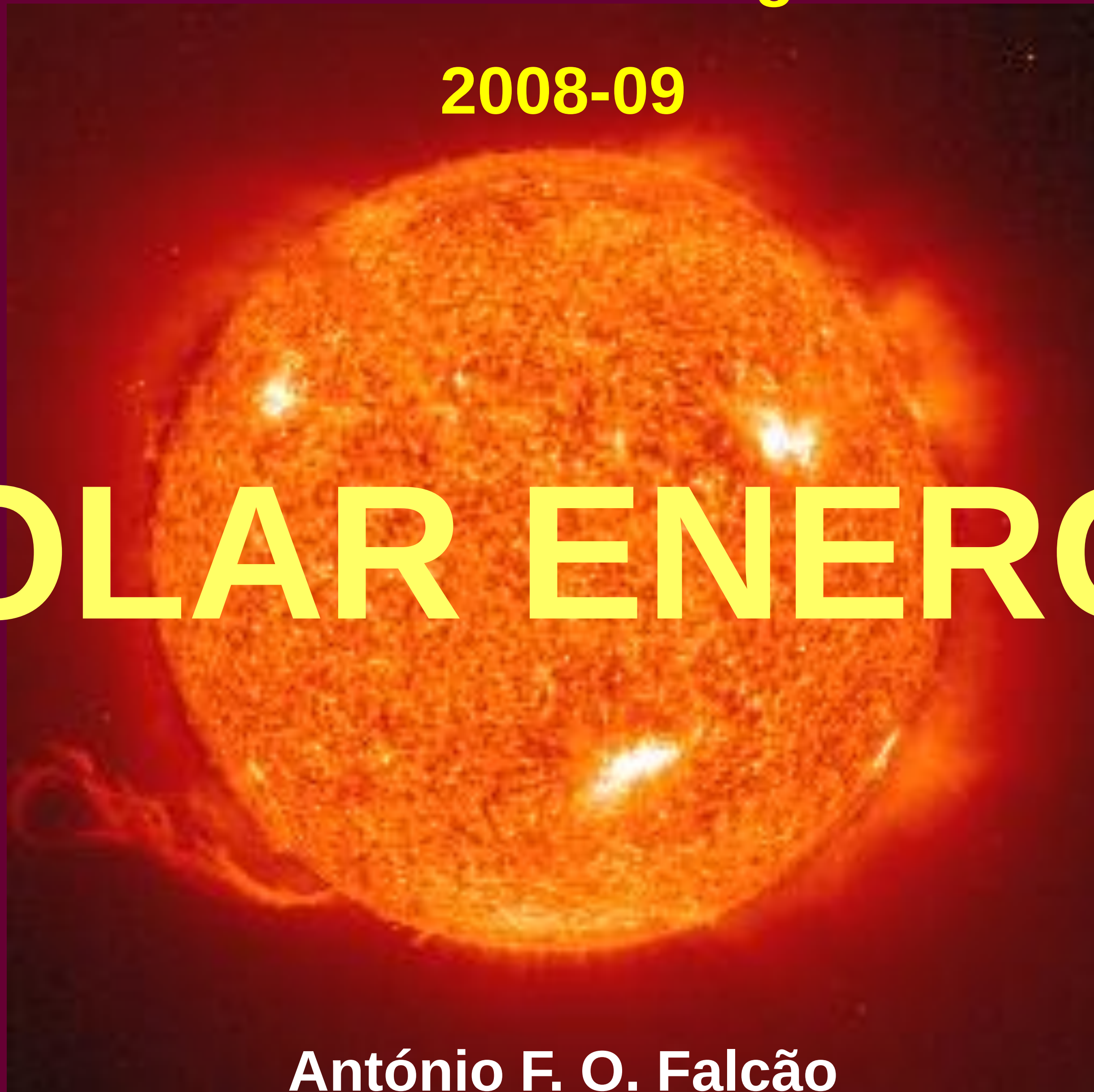
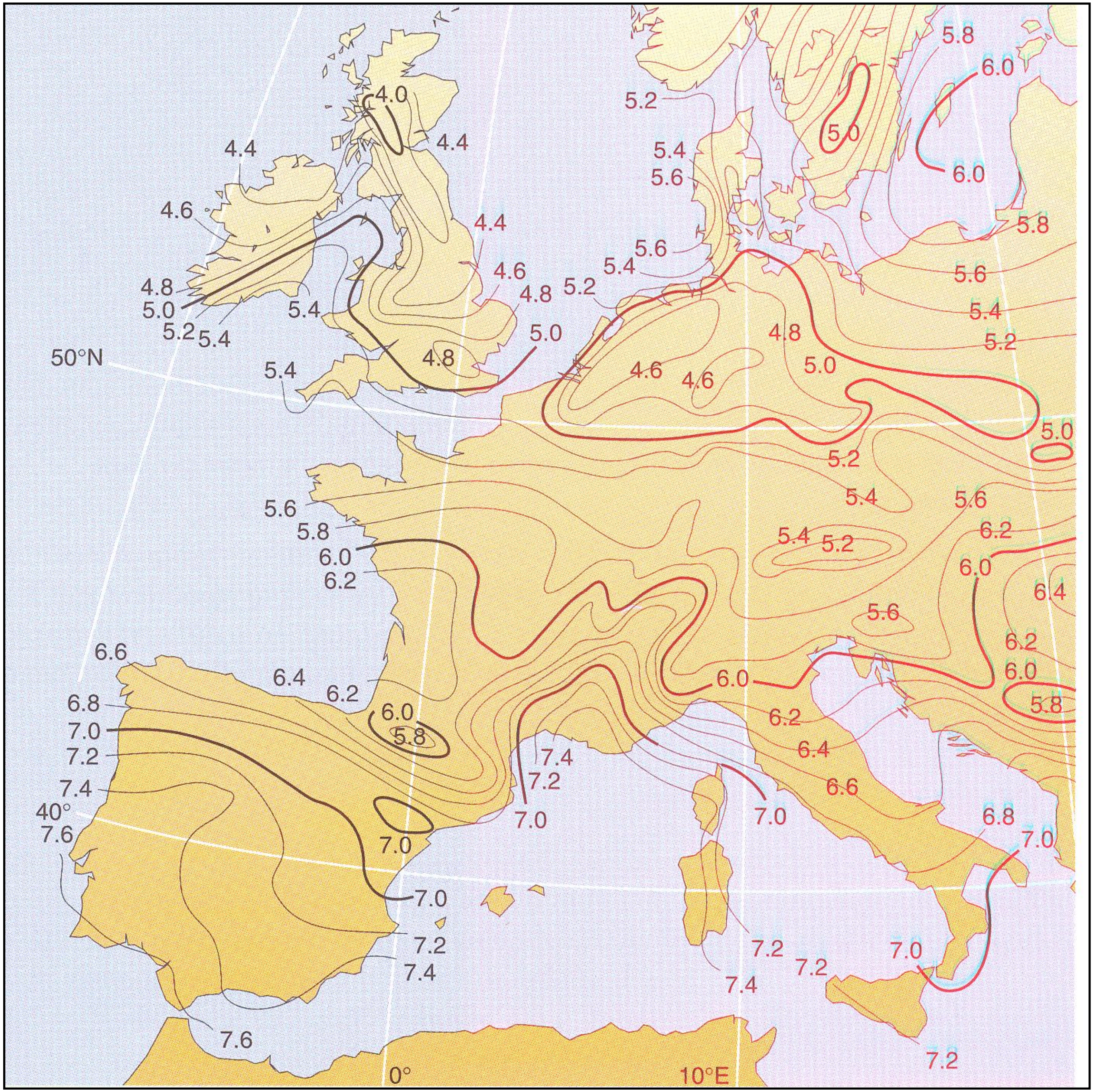
Renewable Energies

2008-09



SOLAR ENERGY

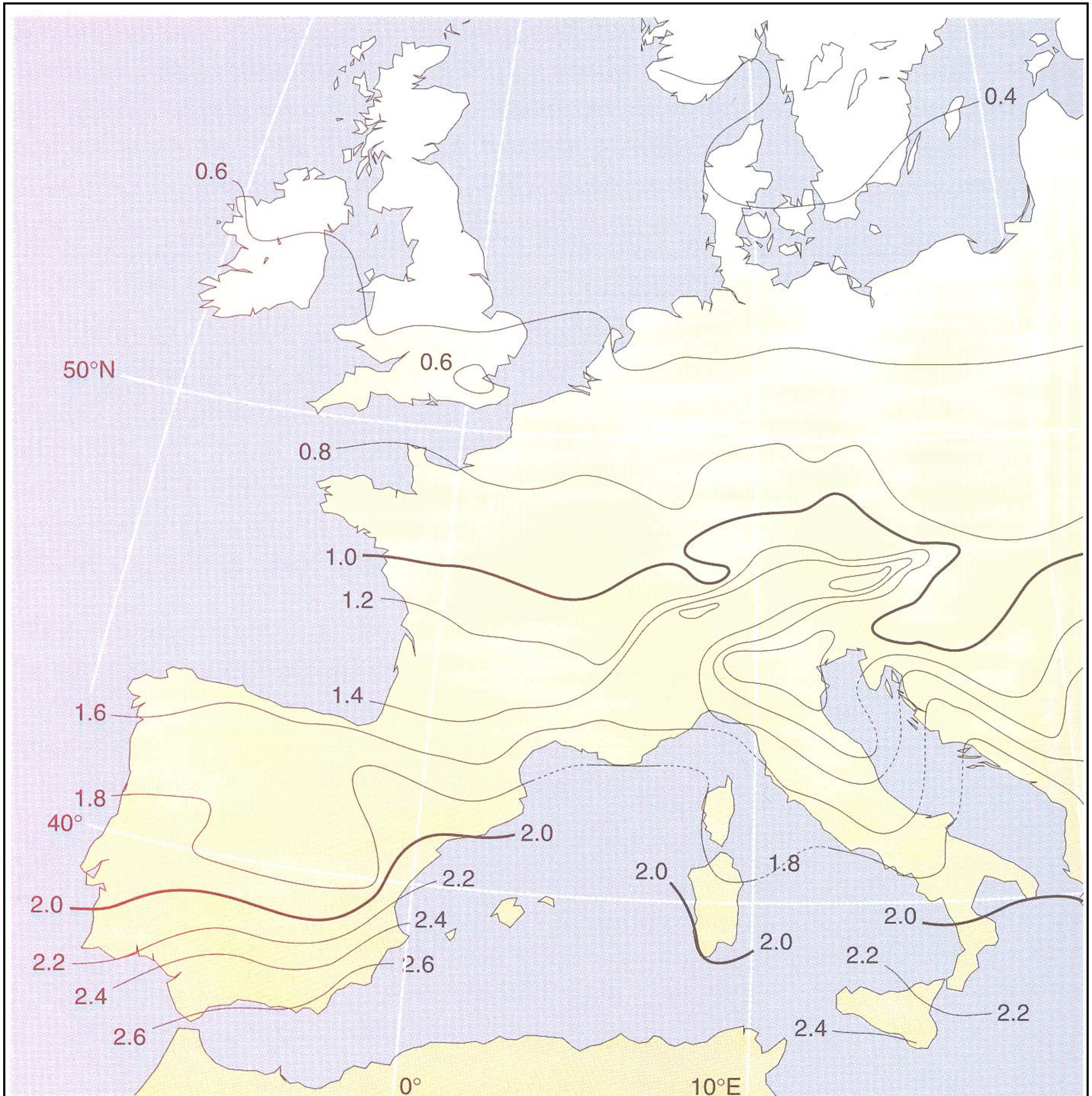
António F. O. Falcão
Instituto Superior Técnico



Solar radiation on horizontal surface

kWh/(m^2.day)

JULY

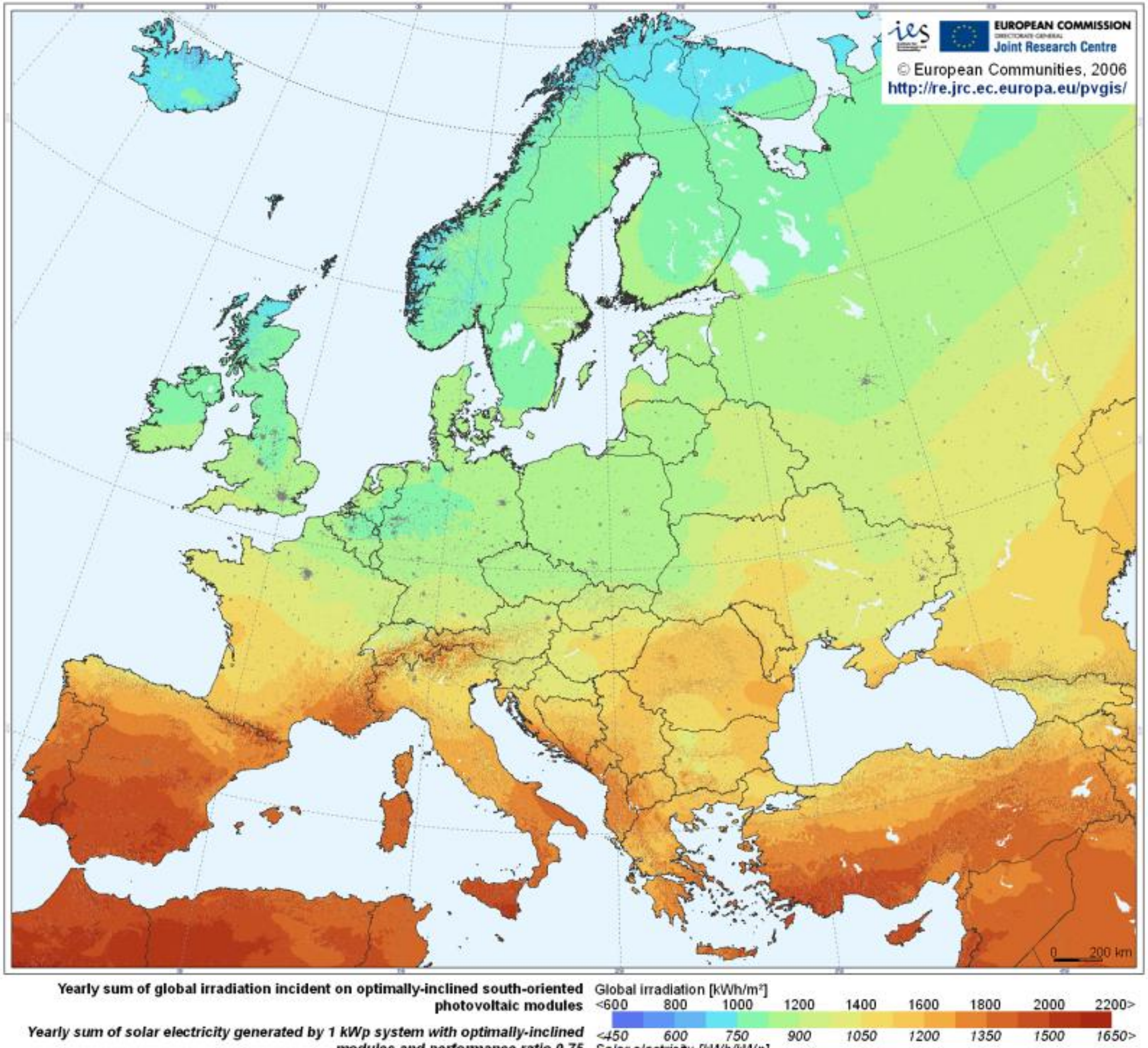


Solar radiation on horizontal surface

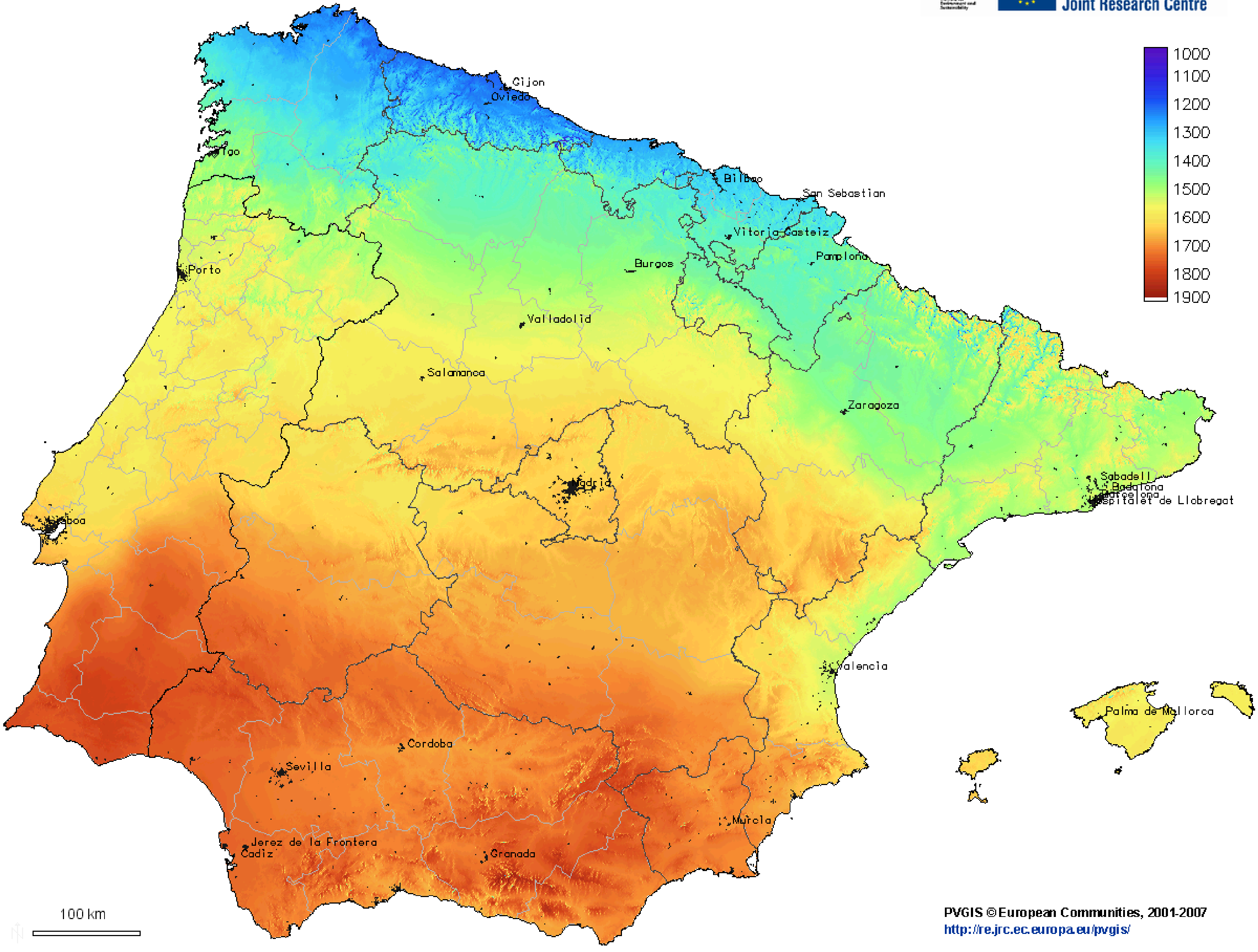
kWh/(m^2.day)

JANUARY

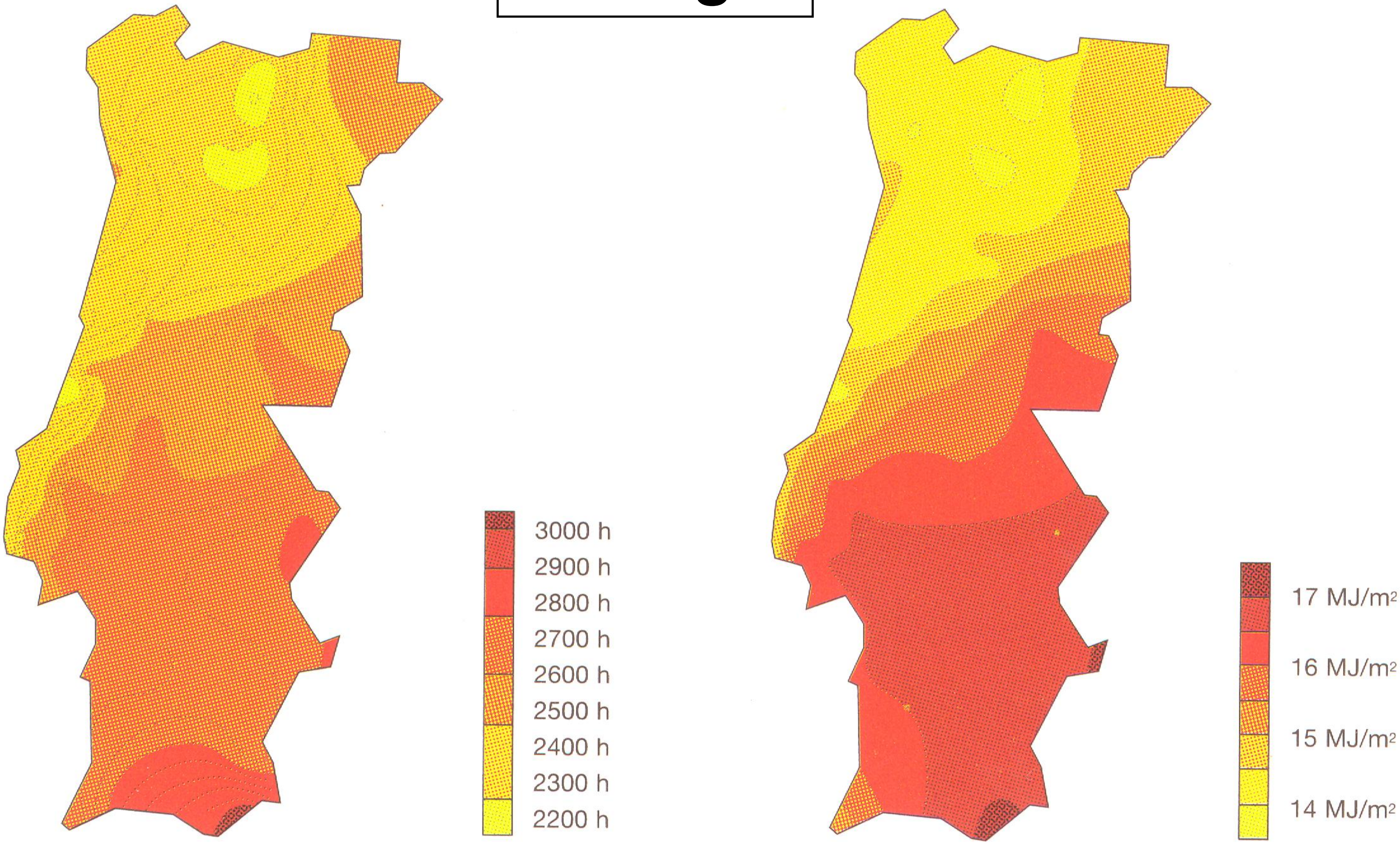
Photovoltaic Solar Electricity Potential in European Countries



Yearly sum of global irradiation on a horizontal surface - Spain and Portugal



Portugal

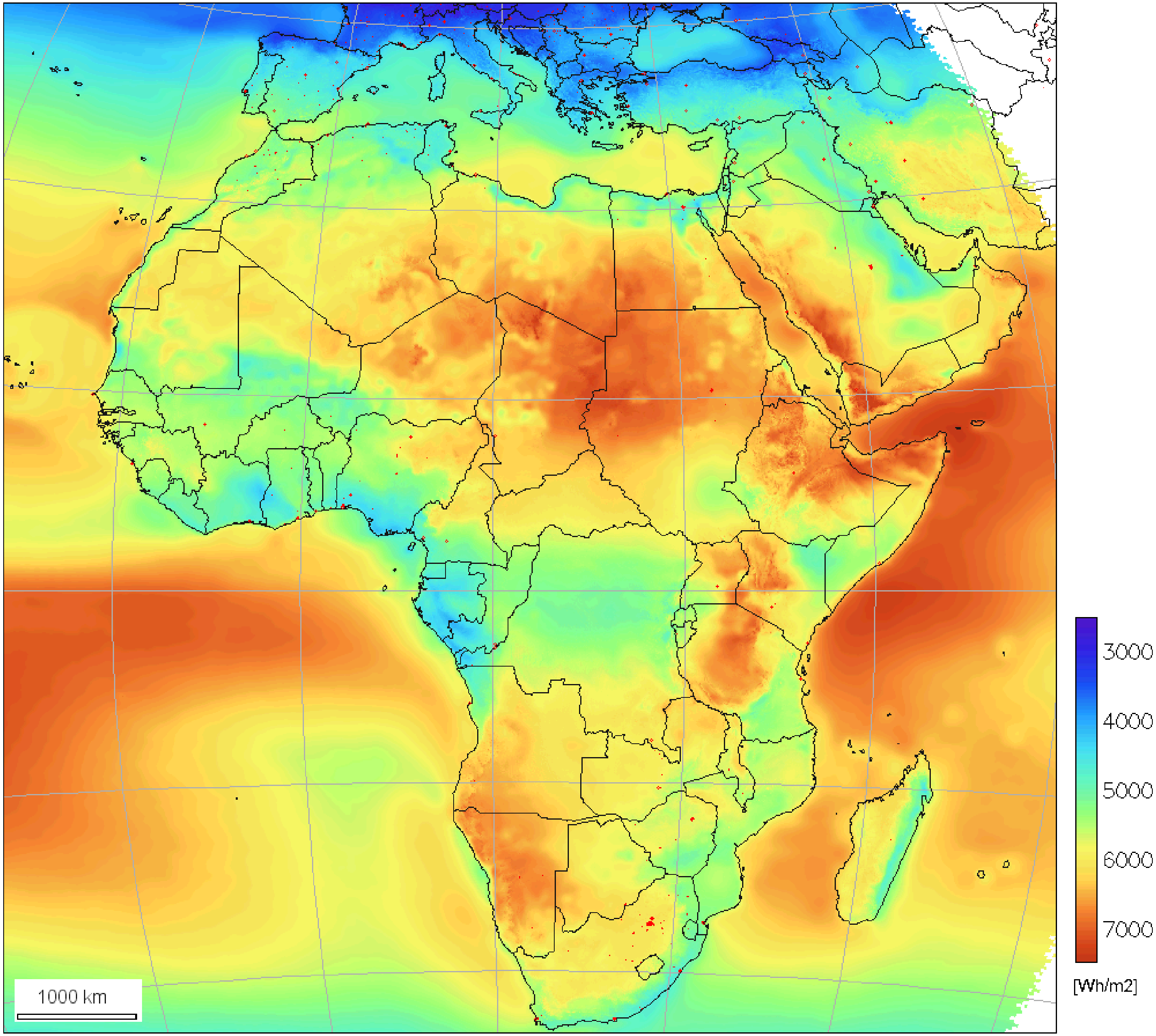


Fonte: Ricardo Aguiar, INETI, 1998

Global horizontal irradiation (1985-2004)
(annual average of daily sums, Gh)

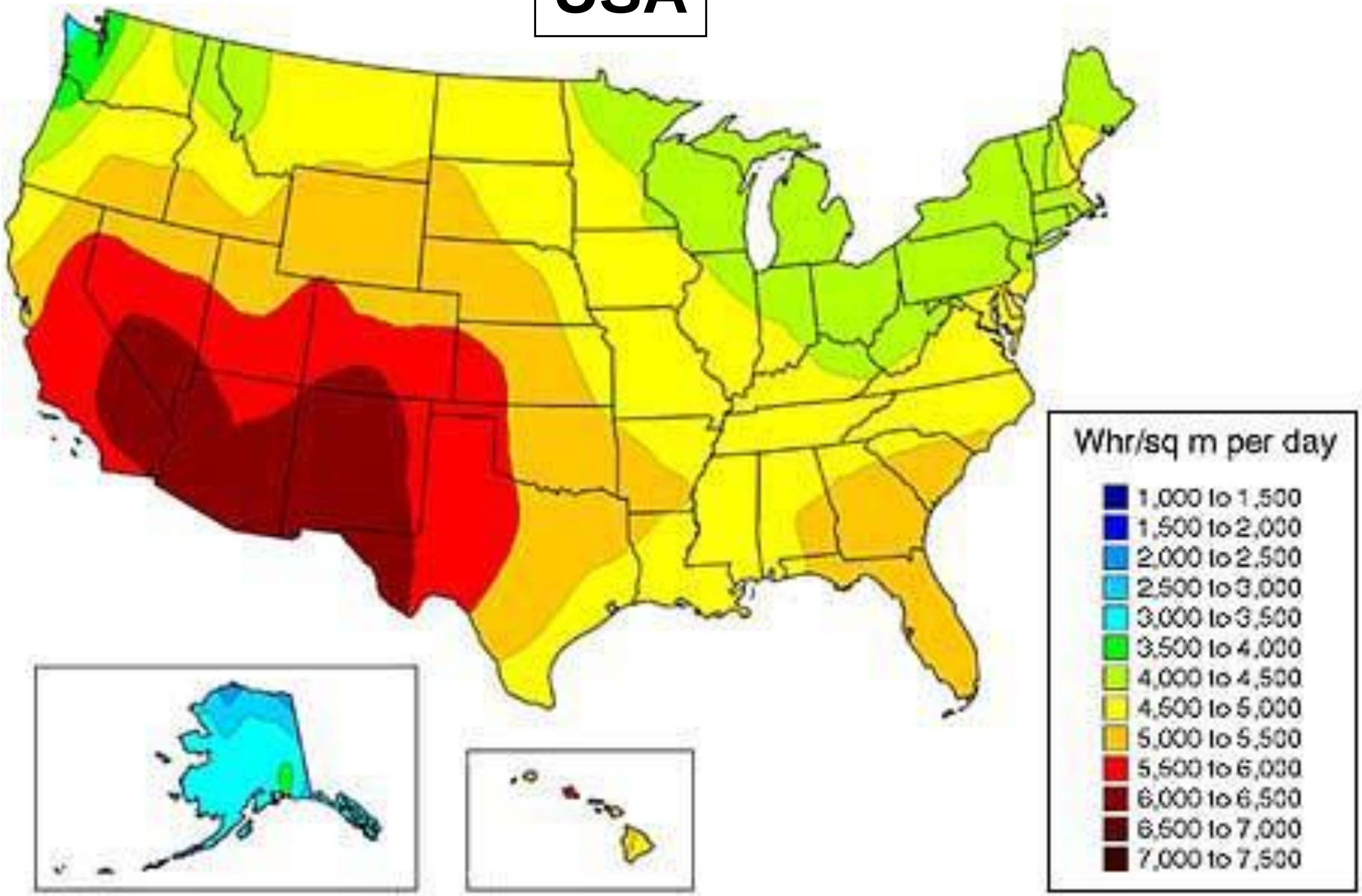
EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

MINES PARIS



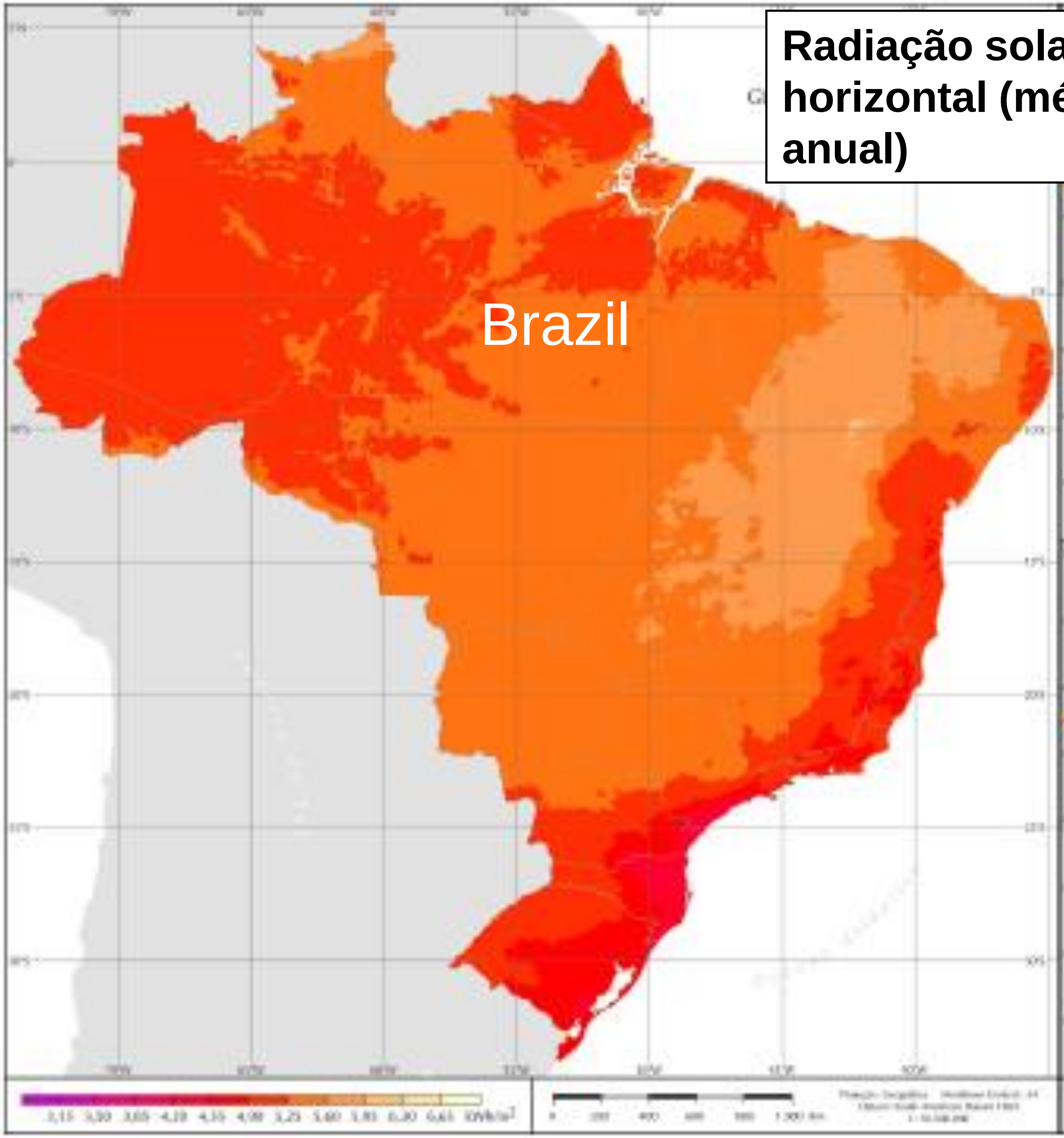
http://re.jrc.ec.europa.eu/pvgis/

USA



Solar resource for a flat-plate collector

Radiação solar global horizontal (média anual)

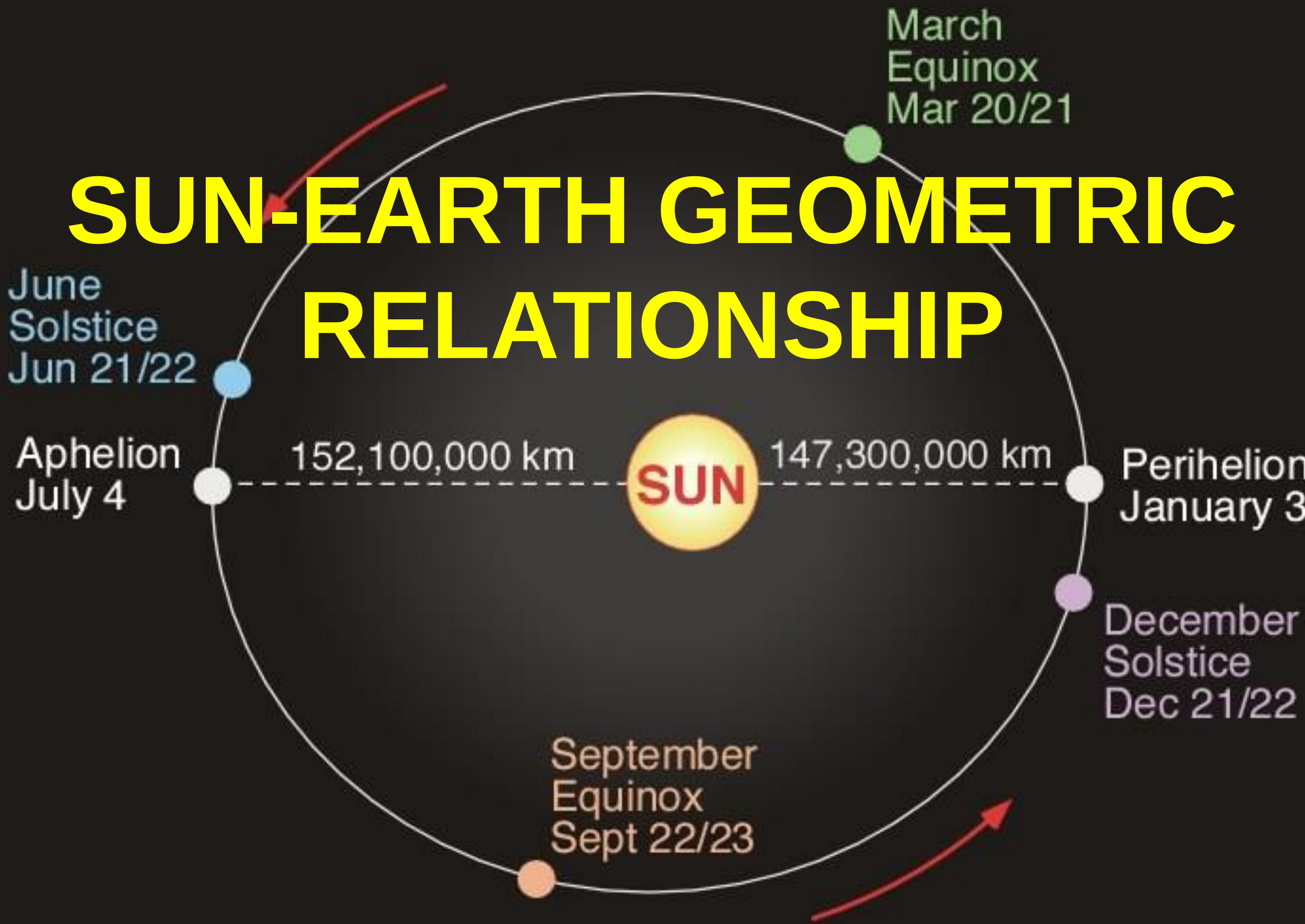


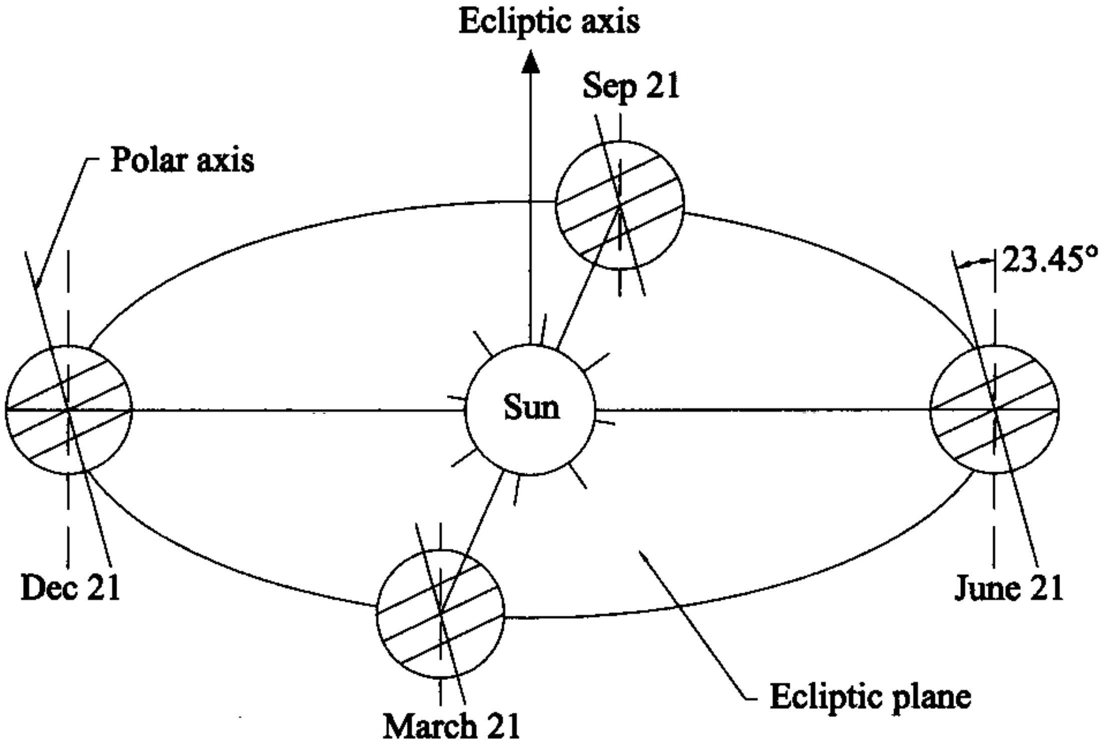
JOINT RESEARCH CENTRE
OF THE EUROPEAN COMMISSION

Maps for solar irradiance in Europe and in European countries available at:

http://re.jrc.ec.europa.eu/pvgis/countries/europe.htm

SUN-EARTH GEOMETRIC RELATIONSHIP

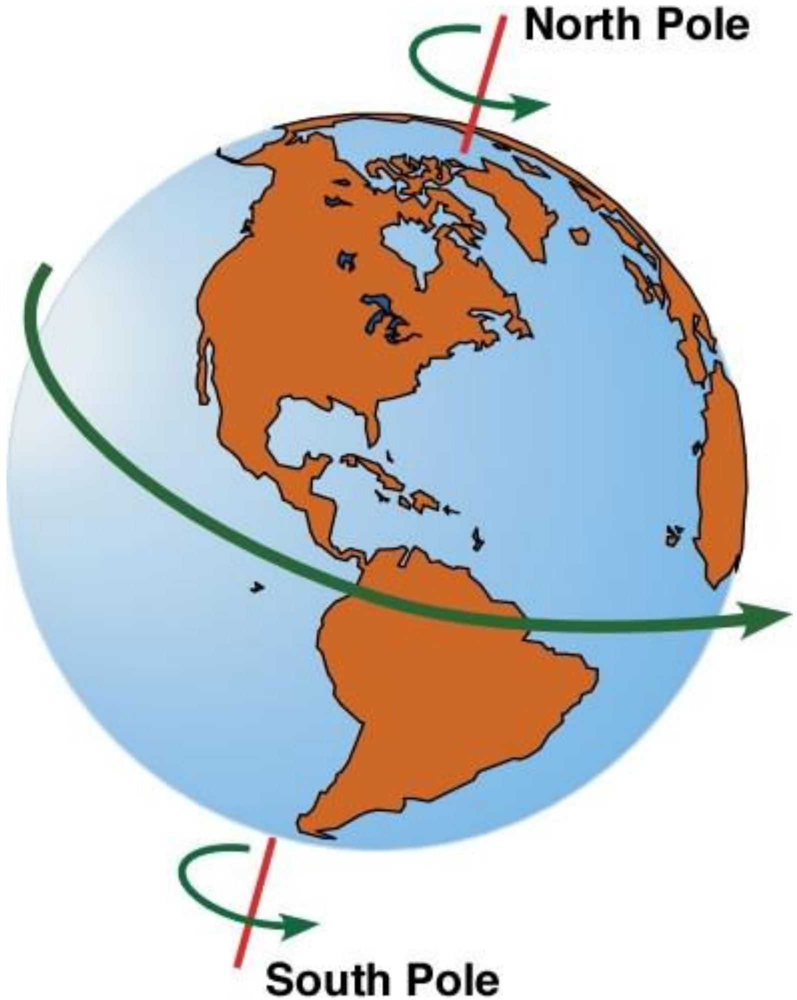


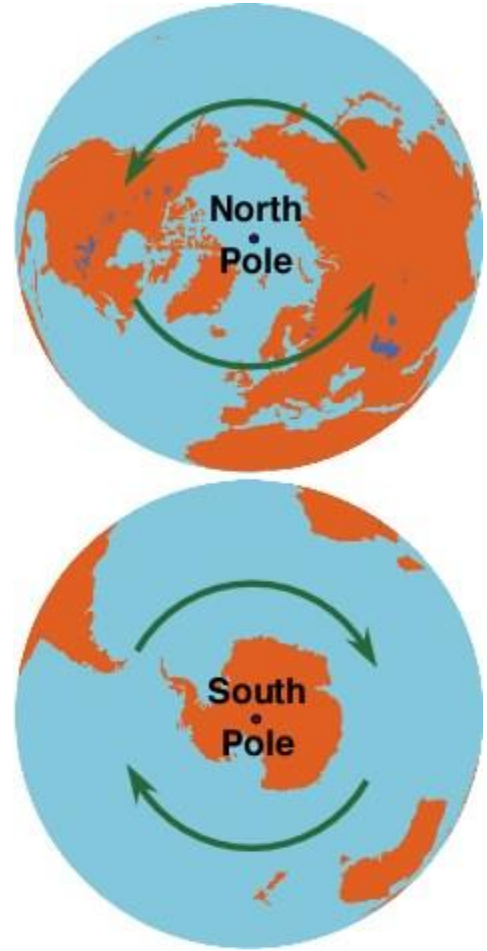


(a)

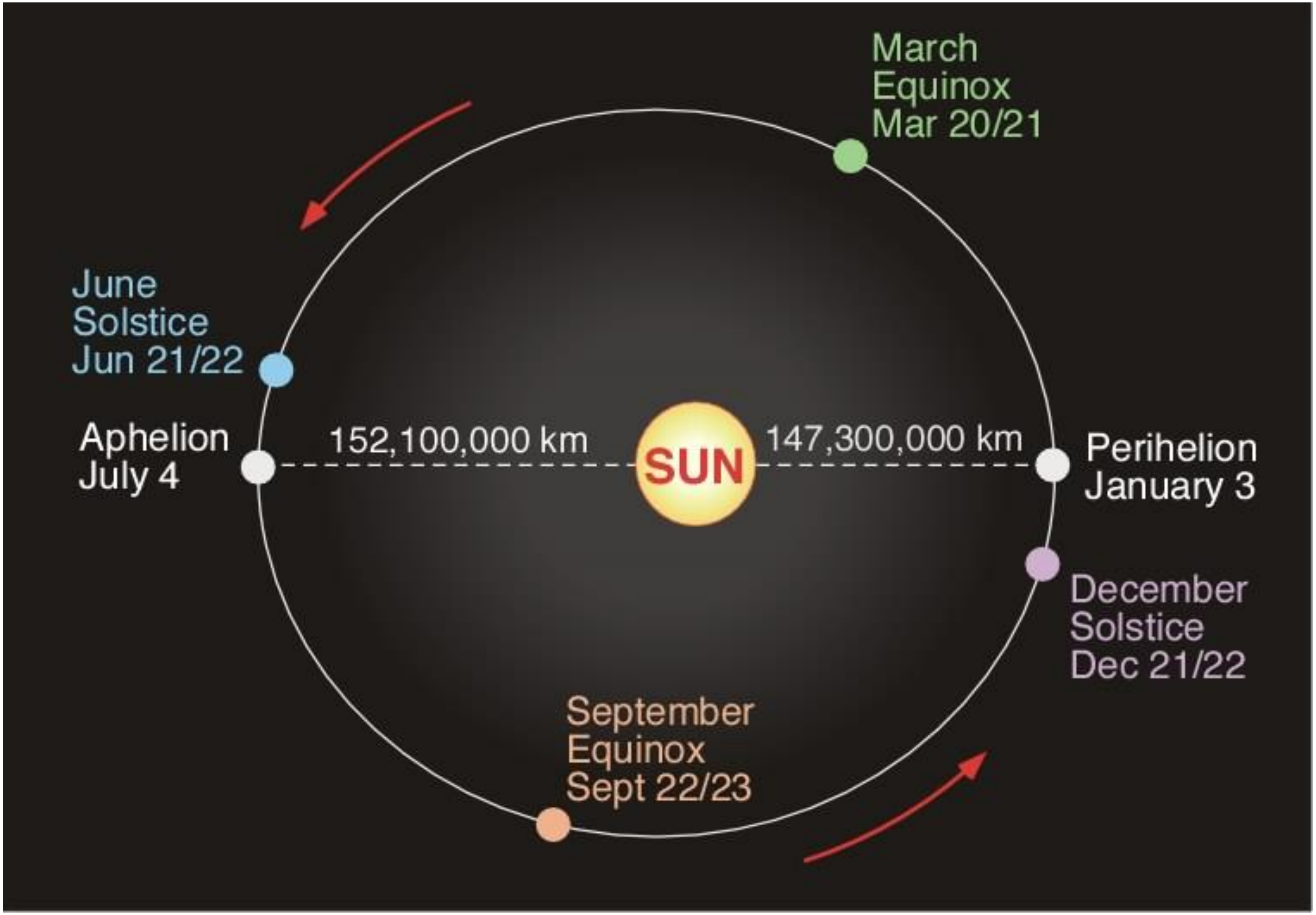
The Earth moves around the Sun along an elliptic orbit (the **Ecliptic**).

- Minimum distance (**perihelion**, 2-3 January): 147.1 10^6 km.
- Maximum distance (**aphelion**, 1-2 July): 152.1×10^6 km.
- Average distance: 149.6×10^6 km.
- Duration of a revolution: 365 days 5 hoursh 48 min 46 s.

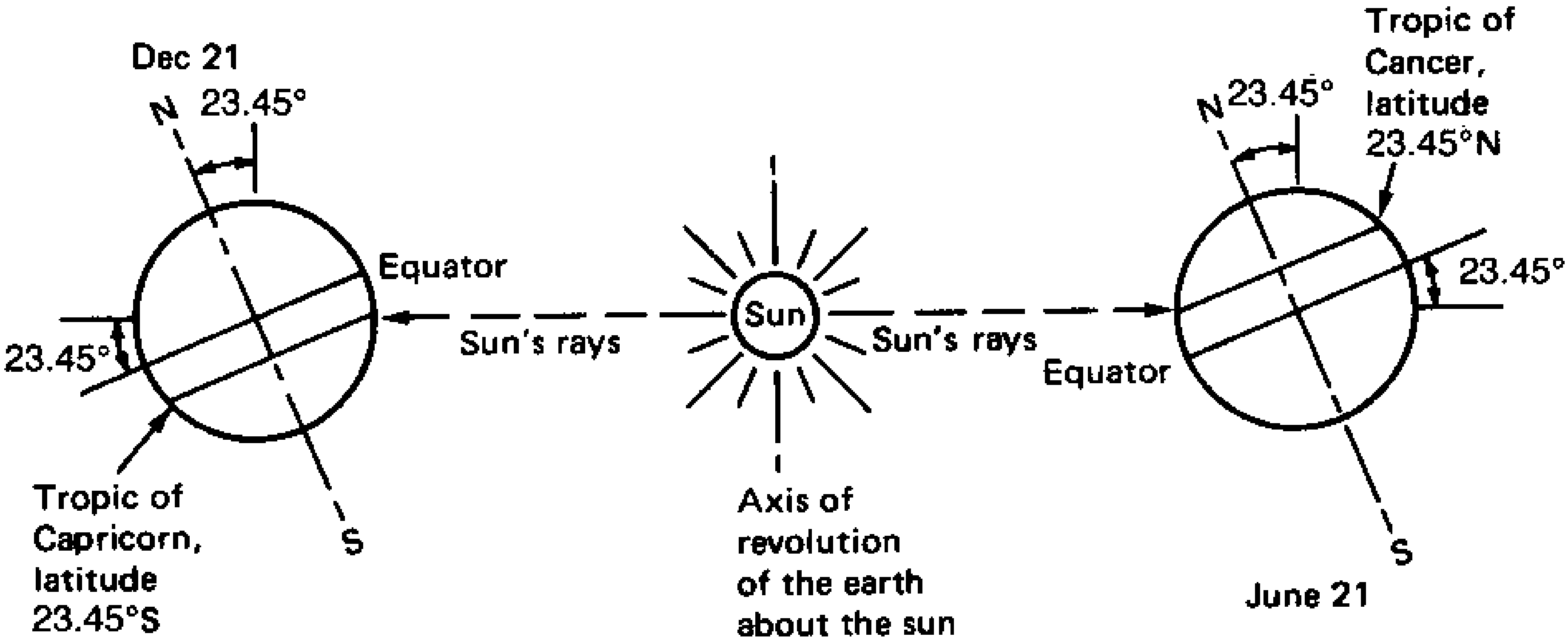




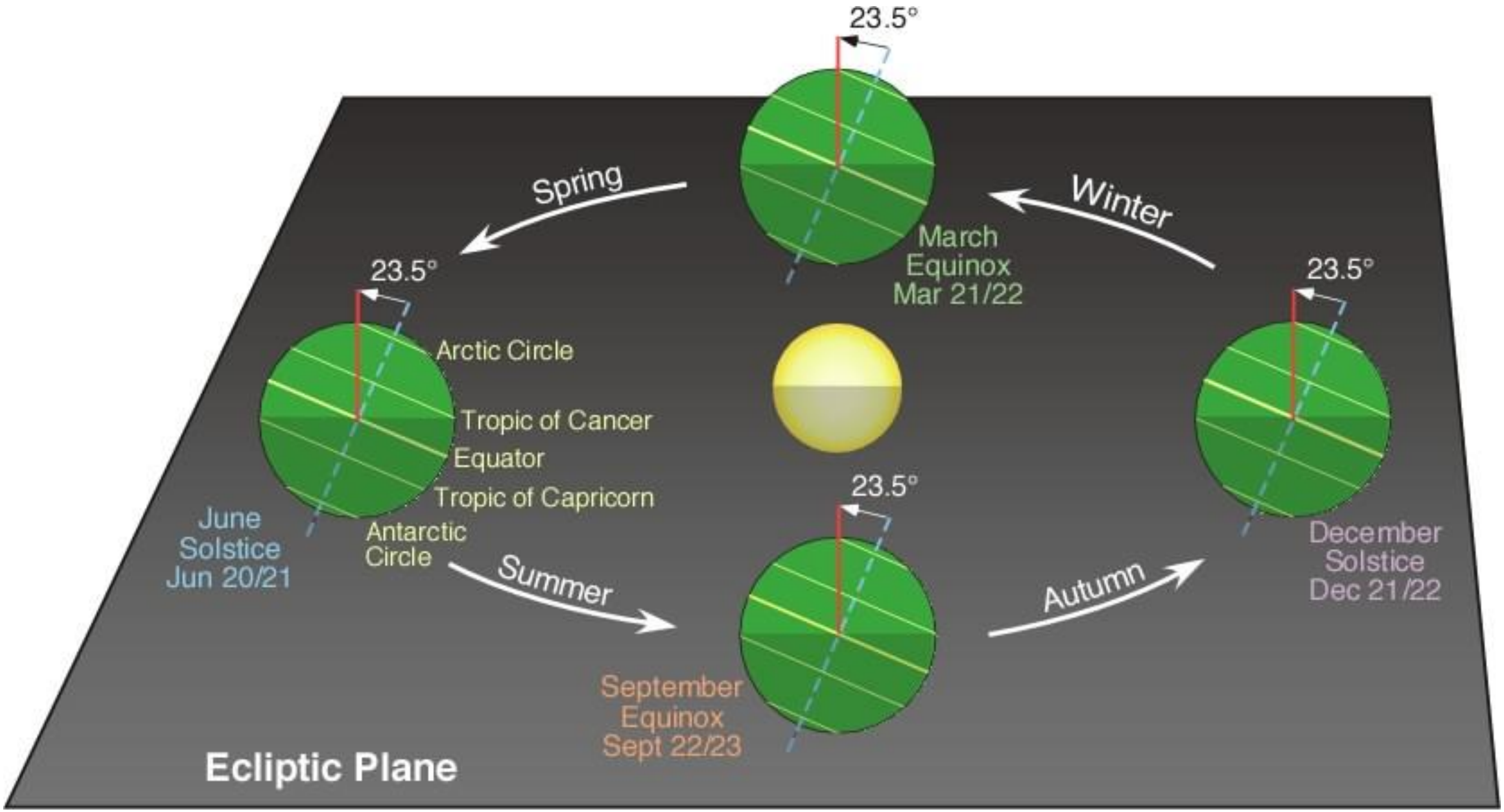
The movement of the Earth about its axis is known as rotation. The direction of this movement varies with the viewer's position. From the North Pole the rotation appears to move in a counter-clockwise fashion. Looking down at the South Pole the Earth's rotation appears clockwise.



Position of the equinoxes, solstices, aphelion, and perihelion relative to the Earth's orbit around the Sun.



- The Earth rotates about its own axis. The axis direction remains unchanged as the Earth moves around the Sun.
- Angle of Earth's axis with normal to ecliptic plan (angle between equatorial plane and ecliptic plane) = **23.45°**.
- This produces the seasonal (summer-winter) variations in the solar radiation on the Earth's surface.



The Earth's rotational axis is tilted 23.45° from the red line drawn perpendicular to the ecliptic plane. This tilt remains the same anywhere along the Earth's orbit around the Sun.

Solar declination δ_s (varies along the year) = angle betweenthe Earth-Sun line (through their centres) and the plane of the equator.

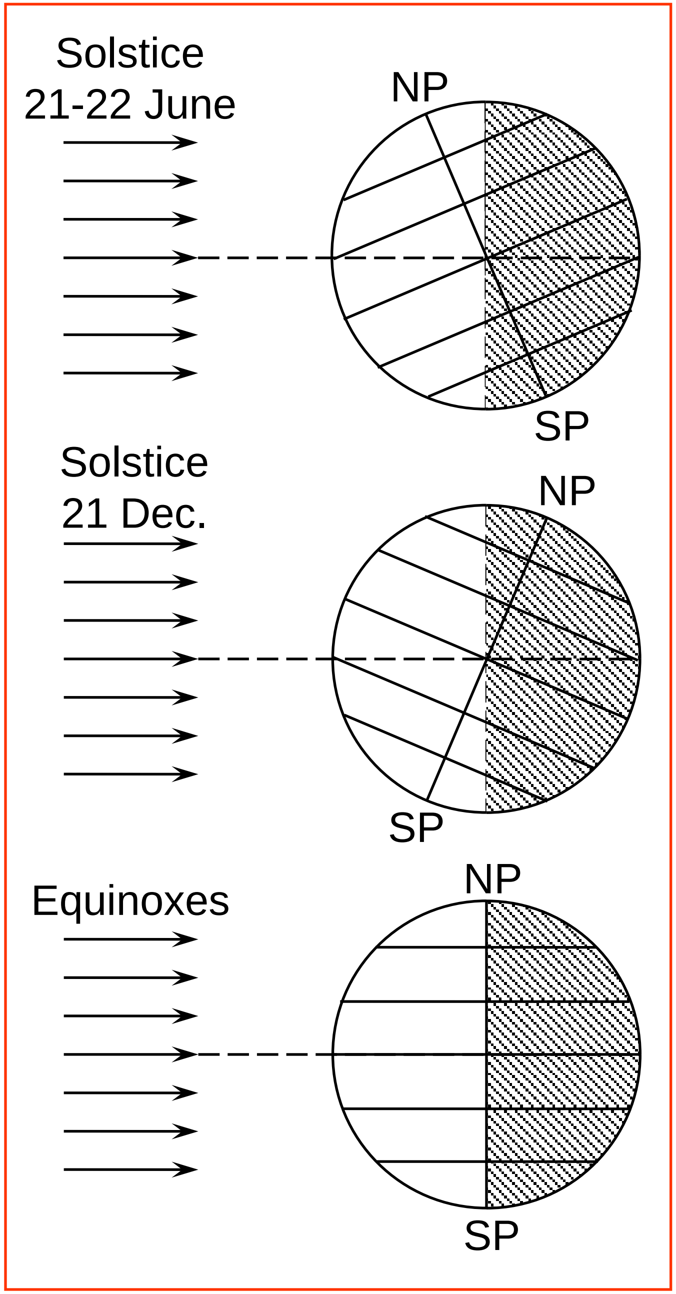
δ_s = − 23.45º in Winter solstice (21 December)

δ_s = + 23.45º in Summer solstice (21 or 22 June)

δ_s = 0 in Spring equinox (20 or 21 March) and Autumn equinox (21 September) (duration of day = duration of night).

Between the tropics of Cancer (23.45º N**)** and Capricorn (23.45º S), the sun rays are vertical at least once a year.

Above the latitudes of the Arctic circle (66.55ºN) and the Antarctic circle (66.55º S) the sun does not rise above the horizon at least once a year.



Annual change in the position of the Earth in its revolution around the Sun

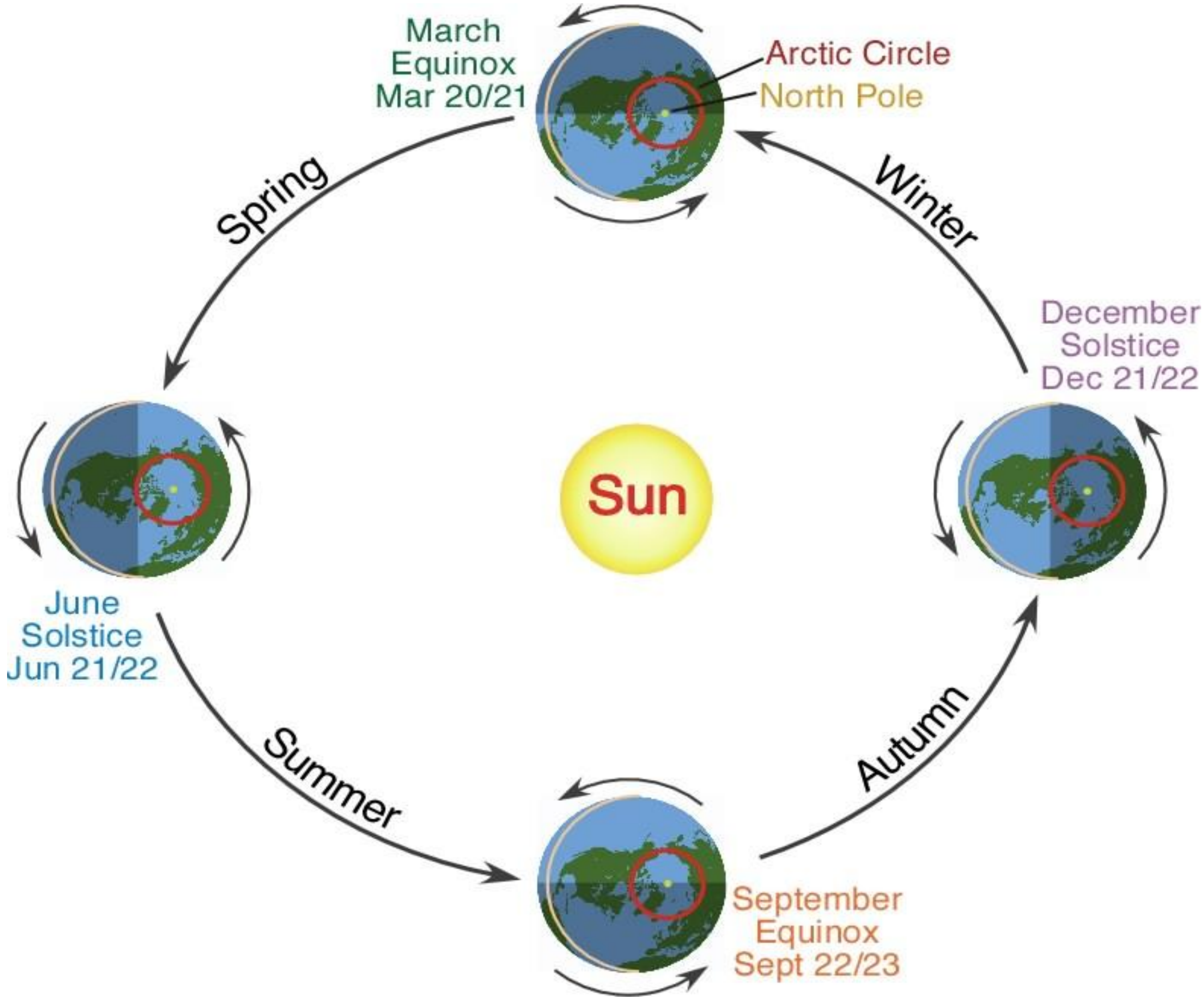
In the following graphic, we are viewing the Earth from a position in space that is above the North Pole (yellow dot) at the summer solstice, the winter solstice, and the two equinoxes.

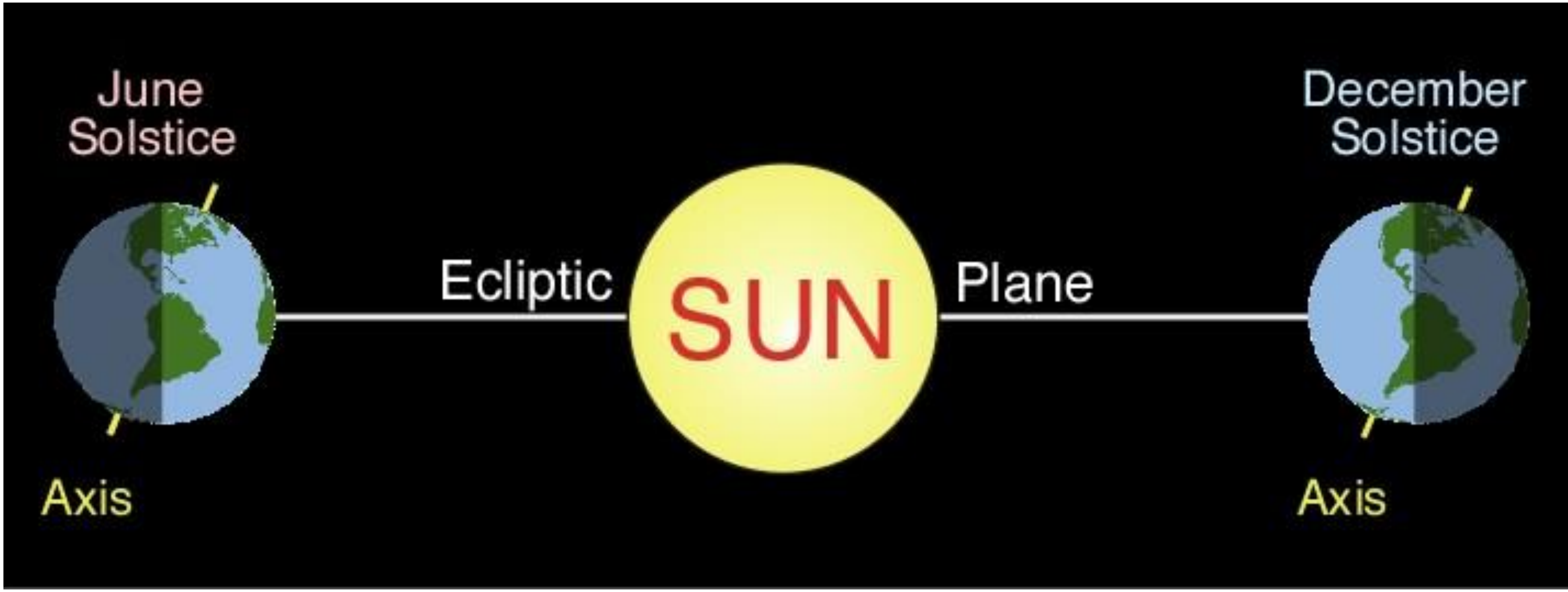
Note how the position of the North Pole on the Earth's surface does not change. However, its position relative to the Sun does change and this shift is responsible for the seasons. The red circle on each of the Earths represents the Arctic Circle (66.55 degrees N).

During the June solstice, the area above the Arctic Circle is experiencing 24 hours of daylight because the North Pole is tilted 23.45 degrees toward the Sun.

The Arctic Circle experiences 24 hours of night when the North Pole is tilted 23.45 degrees away from the Sun in the December solstice.

During the two equinoxes, the circle of illumination cuts through the polar axis and all locations on the Earth experience 12 hours of day and night.

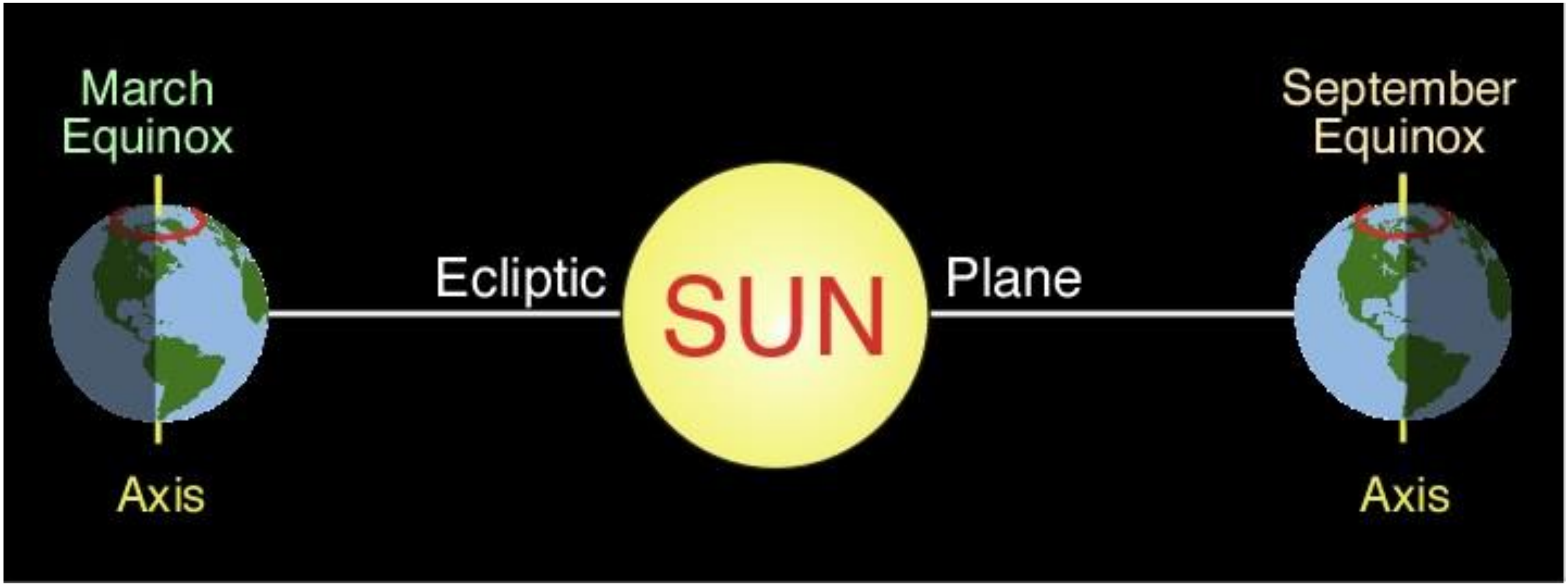

March
Equinox
Mar 20/21
Arctic Circle
North Pole
Spring
Winter
December
Solstice
Dec 21/22
Sun
June
Solstice
Jun 21/22
Summer
Autumn
September
Equinox
Sept 22/23



During the June solstice the Earth's North Pole is tilted 23.45 degrees towards the Sun relative to the circle of illumination.

This phenomenon keeps all places above a latitude of 66.55 degrees N in 24 hours of sunlight, while locations below a latitude of 66.55 degrees S are in darkness.

The North Pole is tilted 23.45 degrees away from the Sun relative to the circle of illumination during the December solstice. On this date, all places above a latitude of 66.55 degrees N are now in darkness, while locations below a latitude of 66.55 degrees S receive 24 hours of daylight.



During the equinoxes, the axis of the Earth is not tilted toward or away from the Sun and the circle of illumination cuts through the poles. This situation does not suggest that the 23.45 degree tilt of the Earth no longer exists.

The vantage point of this graphic shows that the Earth's axis is inclined 23.45 degrees toward the viewer for both dates.

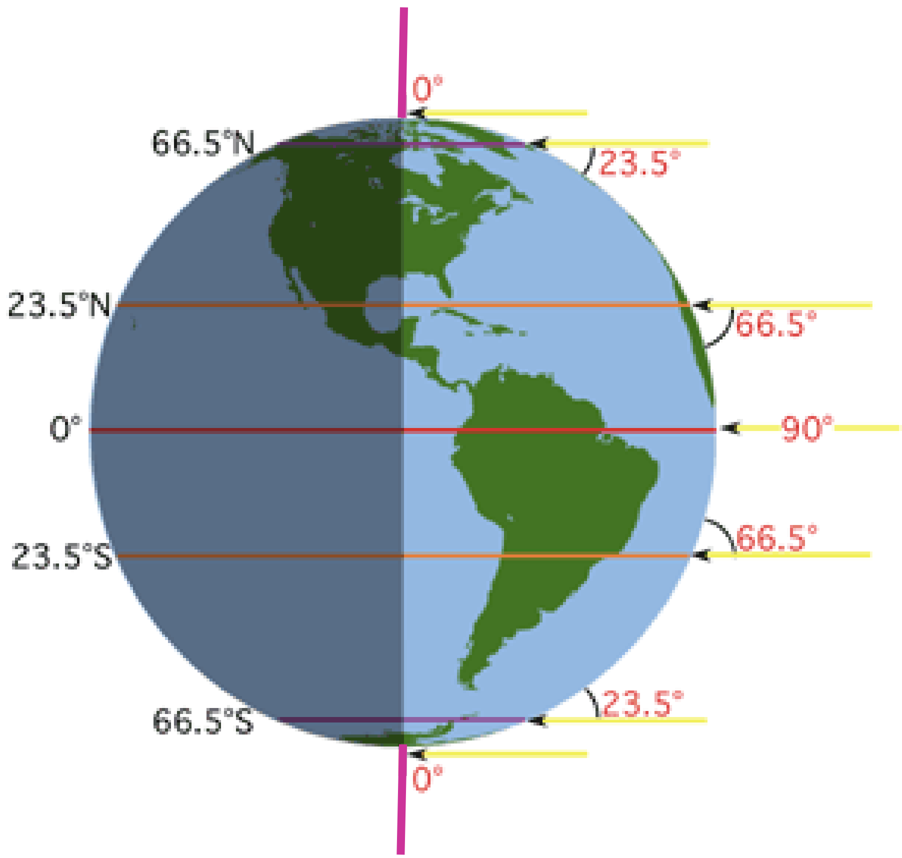
The red circles shown in the graphic are the Arctic Circle.

In the following slide:

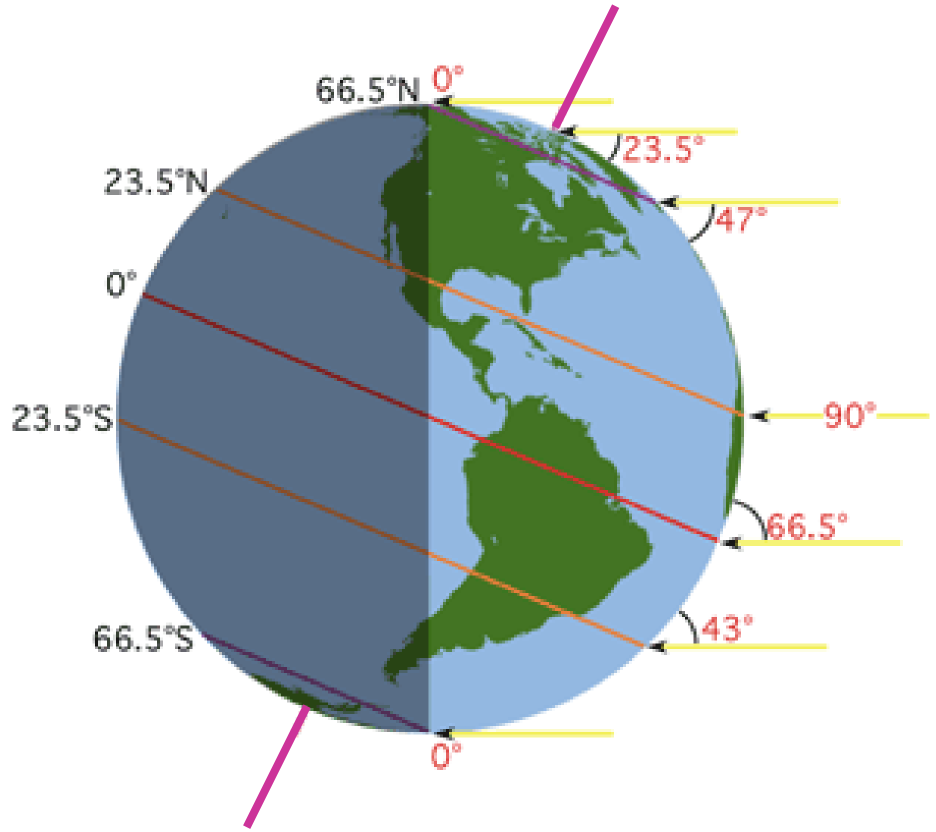
Relationship of maximum Sun height to latitude for the equinox (left) and summer solstice (right). The red values on the right of the globes are maximum solar altitudes at **solar noon**. Black numbers on the left indicate the location of the Equator, Tropic of Cancer (23.45 degrees N), Tropic of Capricorn (23.45 degrees S), Arctic Circle (66.55 degrees N), and the Antarctic Circle (66.55 degrees S).

During the **equinox**, the equator is the location on the Earth with a Sun angle of 90 degrees for solar noon. Note how maximum Sun height declines with latitude as you move away from the Equator. For each degree of latitude traveled maximum Sun height decreases by the same amount. At equinox, you can also calculate the noon angle by subtracting the location's latitude from 90.

During the **summer solstice**, the Sun is now directly overhead at the Tropic of Cancer. All locations above this location have maximum Sun heights that are 23.45 degrees higher from the equinox situation. Places above the Arctic Circle are in 24 hours of daylight. Below the Tropic of Cancer the noon angle of the Sun drops one degree in height for each degree of latitude traveled. At the Antarctic Circle, maximum Sun height becomes 0 degrees and locations south of this point on the Earth are in 24 hours of darkness.



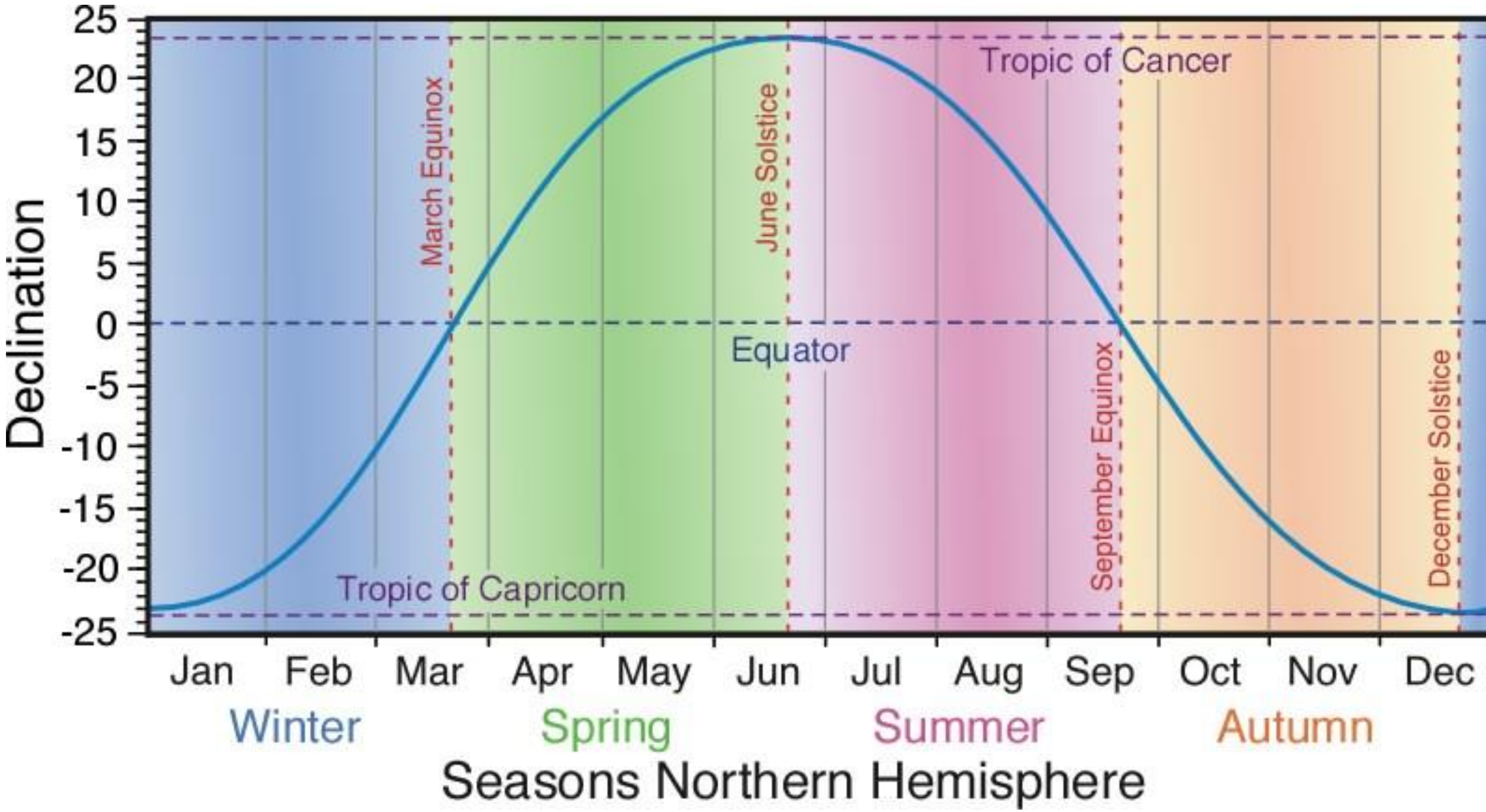
Equinox



Summer solstice

Date		Declination		Equation of Time		Date		Declination		Equation of Time	
		Deg	Min	Min	Sec			Deg	Min	Min	Sec
Jan.	1	−23	4	−3	14	Feb.	1	−17	19	−13	34
	5	22	42	5	6		5	16	10	14	2
	9	22	13	6	50		9	14	55	14	17
	13	21	37	8	27		13	13	37	14	20
	17	20	54	9	54		17	12	15	14	10
	21	20	5	11	10		21	10	50	13	50
	25	19	9	12	14		25	9	23	13	19
	29	18	9	13	5						
Mar.	1	−7	53	−12	38	Apr.	1	+4	14	−4	12
	5	6	21	11	48		5	5	46	3	1
	9	5	48	10	51		9	7	17	1	52
	13	3	14	9	49		13	8	46	−0	47
	17	1	39	8	42		17	10	12	+0	13
	21	−0	5	7	32		21	11	35	1	6
	25	+1	30	6	20		25	12	56	1	53
	29	3	4	5	7		29	14	13	2	33
May	1	+14	50	+2	50	June	1	+21	57	2	27
	5	16	2	3	17		5	22	28	1	49
	9	17	9	3	35		9	22	52	1	6
	13	18	11	3	44		13	23	10	+0	18
	17	19	9	3	44		17	23	22	−0	33
	21	20	2	3	24		21	23	27	1	25
	25	20	49	3	16		25	23	25	2	17
	29	21	30	2	51		29	23	17	3	7

Date		Declination Deg	Declination Min	Equation of Time Min	Equation of Time Sec	Date		Declination Deg	Declination Min	Equation of Time Min	Equation of Time Sec
July	1	+23	10	−3	31	Aug.	1	+18	14	−6	17
	5	22	52	4	16		5	17	12	5	59
	9	22	28	4	56		9	16	6	5	33
	13	21	57	5	30		13	14	55	4	57
	17	21	21	5	57		17	13	41	4	12
	21	20	38	6	15		21	12	23	3	19
	25	19	50	6	24		25	11	2	2	18
	29	18	57	6	23		29	9	39	1	10
Sep.	1	+8	35	−0	15	Oct.	1	−2	53	+10	1
	5	7	7	+1	2		5	4	26	11	17
	9	5	37	2	22		9	5	58	12	27
	13	4	6	3	45		13	7	29	13	30
	17	2	34	5	10		17	8	58	14	25
	21	1	1	6	35		21	10	25	15	10
	25	0	32	8	0		25	11	50	15	46
	29	2	6	9	22		29	13	12	16	10
Nov.	1	−14	11	+16	21	Dec.	1	−21	41	11	16
	5	15	27	16	23		5	22	16	9	43
	9	16	38	16	12		9	22	45	8	1
	13	17	45	15	47		13	23	6	6	12
	17	18	48	15	10		17	23	20	4	47
	21	19	45	14	18		21	23	26	2	19
	25	20	36	13	15		25	23	25	+0	20
	29	21	21	11	59		29	23	17	−1	39



Angle of the Sun's declination δ_s. Seasons are for the Northern Hemisphere.

In Solar Energy studies, we adopt the Earth as the reference frame (assume that the Sun rotates about the Earth).

At a given place and time, the position of the Sun is determined by two angular coordinates:

- **Solar altitude angle** $\boldsymbol{\alpha}$: between sun rays and the horizontal plane.
- **Solar azimuth angle** $\boldsymbol{a_s}$: between the projection of sun rays on the horizontal plane and the North-South direction.
- It is $a_s < 0$ before noon (solar time), and $a_s > 0$ after noon.
- The solar zenith angle, *z*, is the angle between the sun rays and the local vertical direction. It is $z = 90° - \alpha$.

- The **local standard time** (time shown on the clocks) is in general different from **local solar time**.

- The difference depends on longitude, on conventions and country regulations (summer, winter time) and on day of the year.

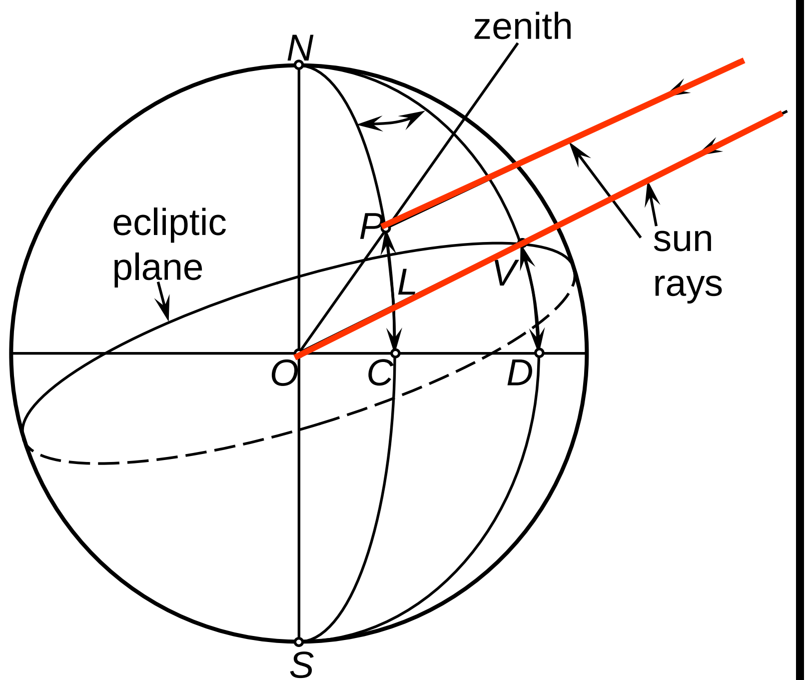
- **For details on calculation, see written text.**

The solar altitude angle α and the solar azimuth angle a_s can be expressed as functions of the three fundamental angles:

- **The solar hour angle** $h_s = 15° \times$ (time, in hours, since solar noon). It is $h_s < 0$ in the morning (before solar noon) and $h_s > 0$ in the afternoon.

- **The latitude** L (depends on site).

- **The solar declination** δ_s (depends on day of year).



$h_s = \text{angle}(CND)$

$\delta_s = \text{angle}\ (VOD)$

$L = \text{angle}\ (POC)$

From (three-dimensional) trigonometric relations, we can obtain:

$$\boxed{\sin\alpha = \sin L \sin\delta_s + \cos L \cos\delta_s \cos h_s} \tag{1}$$

$$\boxed{\sin a_s = \frac{\cos\delta_s \sin h_s}{\cos\alpha}} \tag{2}$$

At solar noon, it is $h_s = 0$ and so $a_s = 0$ and $\alpha = 90° - |L - \delta_s|$

Maximum Sun altitudes (at noon) for selected latitudes during the two solstices and equinoxes.

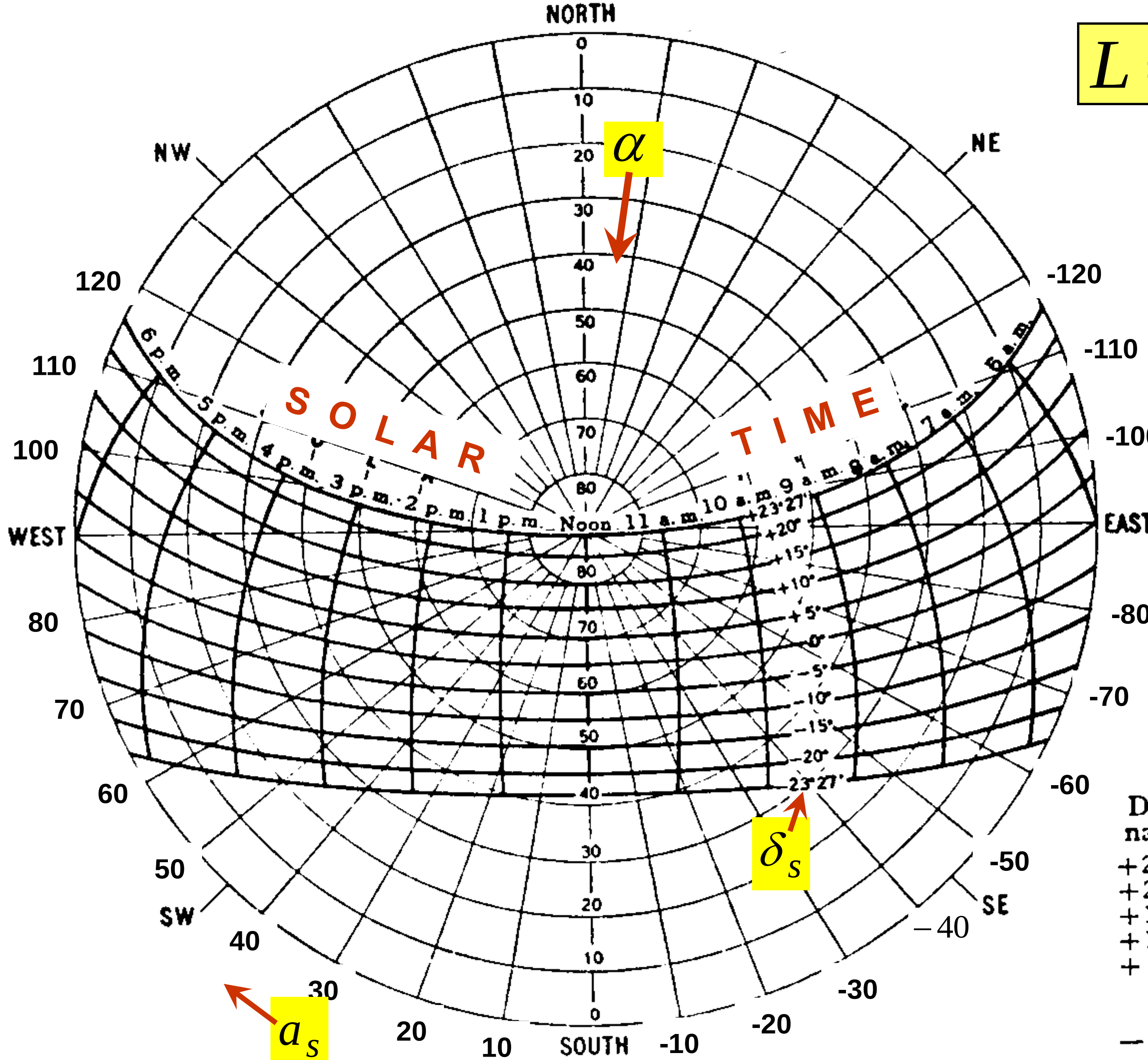
Location's Latitude	March Equinox March 20/21	June Solstice June 21/22	September Equinox September 22/23	December Solstice December 21/22
90 N	0 degrees	23.5 degrees	0 degrees	- 23.5 degrees
70 N	20 degrees	43.5 degrees	20 degrees	-3.5 degrees
66.5 N	23.5 degrees	47 degrees	23.5 degrees	0 degrees
60 N	30 degrees	53.5 degrees	30 degrees	6.5 degrees
50 N	40 degrees	63.5 degrees	40 degrees	16.5 degrees
23.5 N	66.5 degrees	90 degrees	66.5 degrees	43 degrees
0 degrees	90 degrees	66.5 degrees	90 degrees	66.5 degrees
23.5 S	66.5 degrees	43 degrees	66.5 degrees	90 degrees
50 S	40 degrees	16.5 degrees	40 degrees	63.5 degrees
60 S	30 degrees	6.5 degrees	30 degrees	53.5 degrees
66.5 S	23.5 degrees	0 degrees	23.5 degrees	47 degrees
70 S	20 degrees	-3.5 degrees	20 degrees	43.5 degrees
90 S	0 degrees	- 23.5 degrees	0 degrees	23.5 degrees

SUN-PATH DIAGRAMS

Each of the following six diagrams (for latitudes L = 25, 30, 35, 40, 45 and 50 degrees) represent the solar angles (α, a_s) (that define the position of the Sun with respect to the Earth) as functions of the solar hour (or of solar hour angle h_s) and of solar declination δ_s .

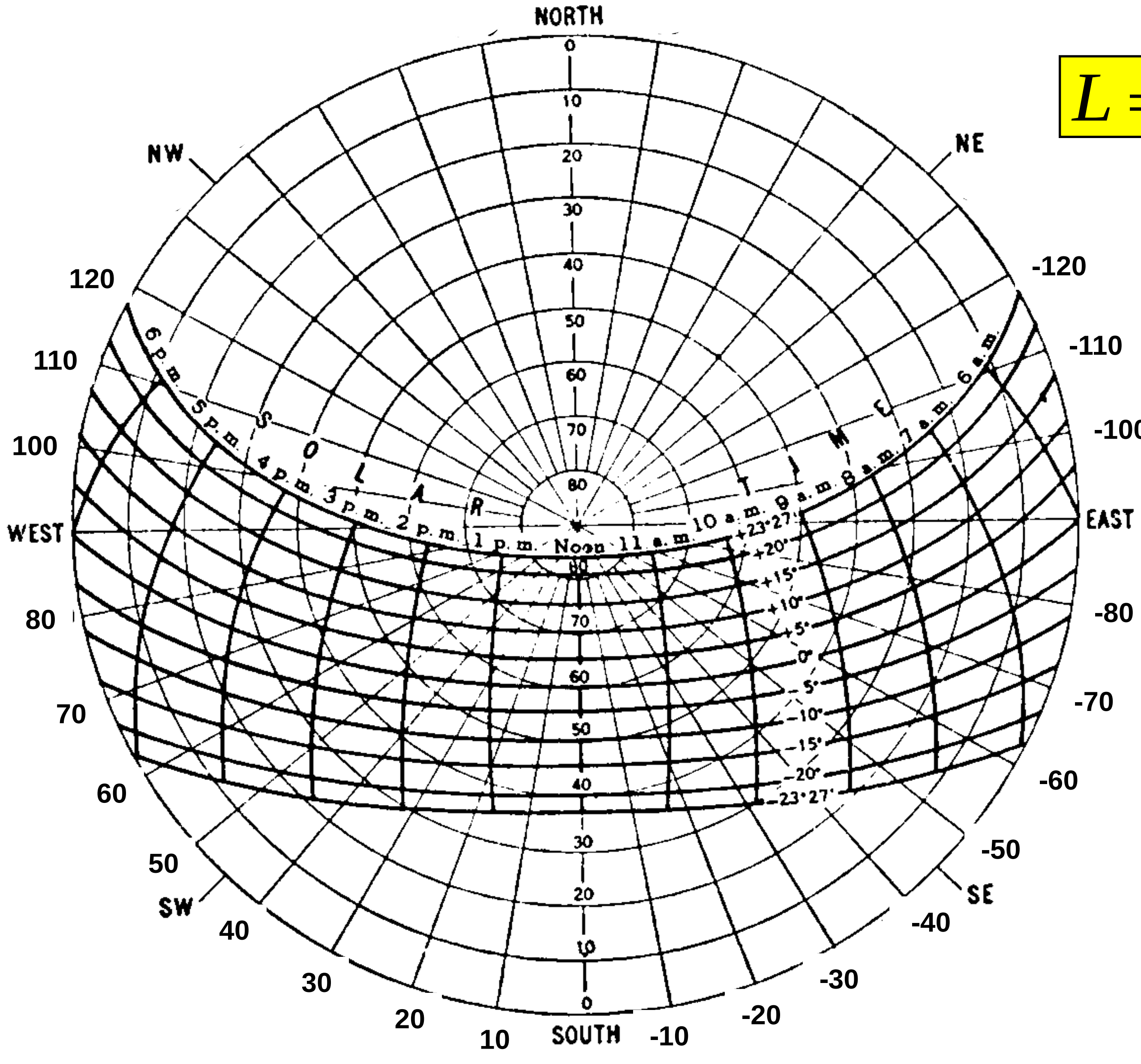
The legends are given on the first diagram (L = 25 degrees).

$L = 25°N$

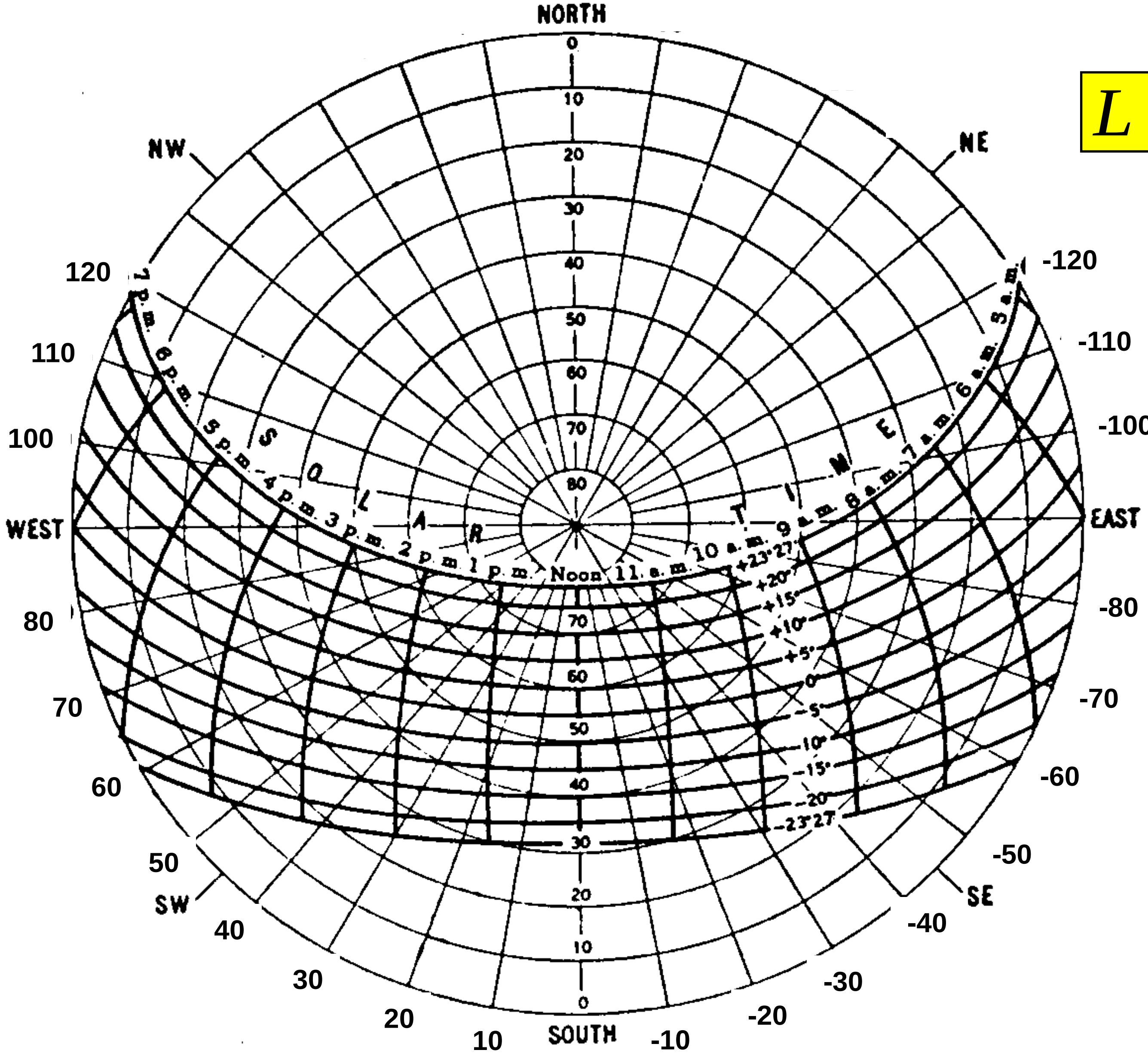


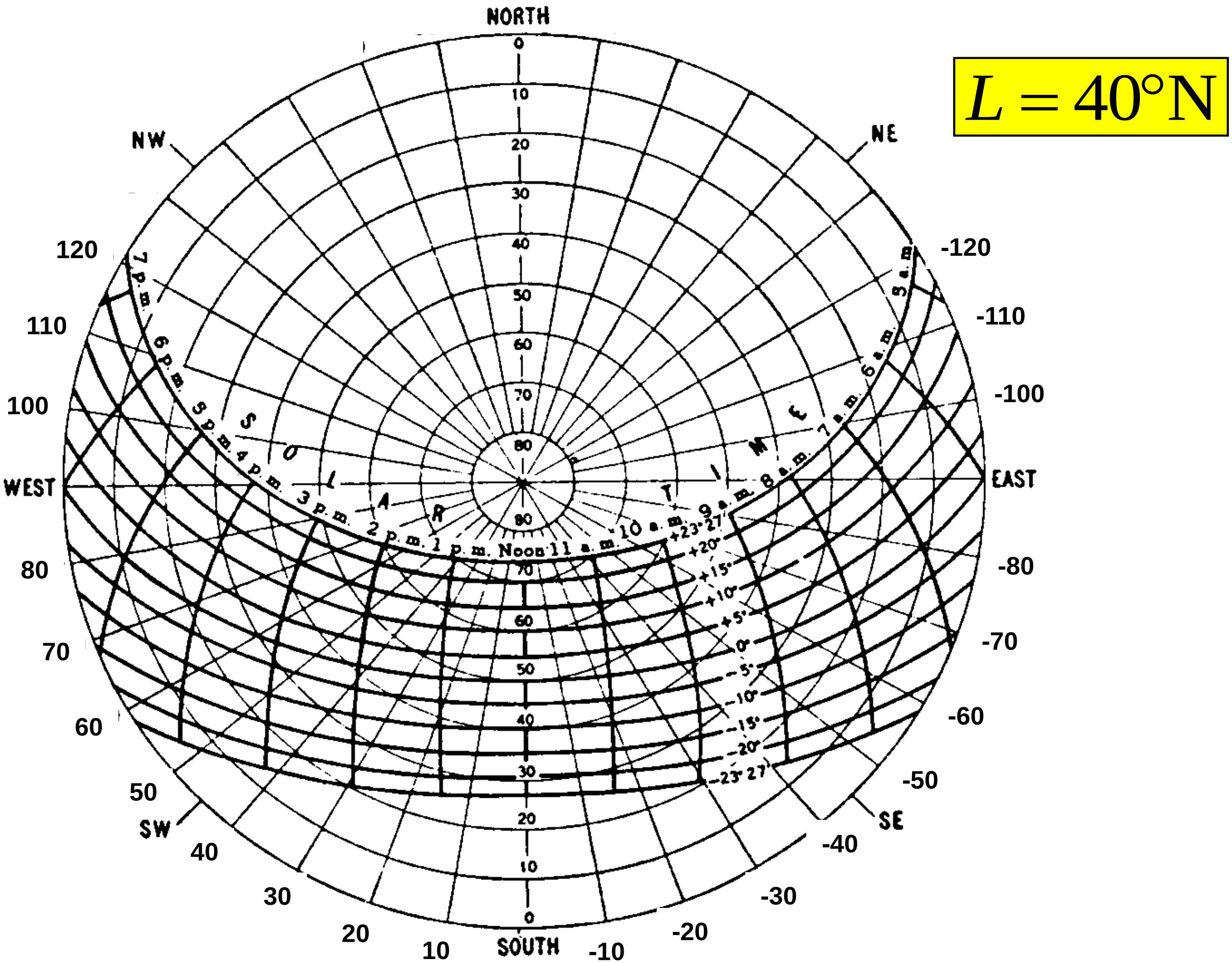
Declination	Approx. dates
+23° 27′	June 22
+20°	May 21, July 24
+15°	May 1, Aug. 12
+10°	Apr. 16, Aug. 28
+ 5°	Apr. 3, Sept. 10
0°	Mar. 21, Sept. 23
− 5°	Mar. 8, Oct. 6
−10°	Feb. 23, Oct. 20
−15°	Feb. 9, Nov. 3
−20°	Jan. 21, Nov. 22
−23° 27′	Dec. 22

$L = 30°\mathrm{N}$


NORTH
NE
EAST
SE
SOUTH
SW
WEST
NW
SOLAR TIME
6 p.m. 5 p.m. 4 p.m. 3 p.m. 2 p.m. 1 p.m. Noon 11 a.m. 10 a.m. 9 a.m. 8 a.m. 7 a.m. 6 a.m.
+23°27' +20° +15° +10° +5° 0° -5° -10° -15° -20° -23°27'
120 110 100 80 70 60 50 40 30 20 10
-10 -20 -30 -40 -50 -60 -70 -80 -100 -110 -120

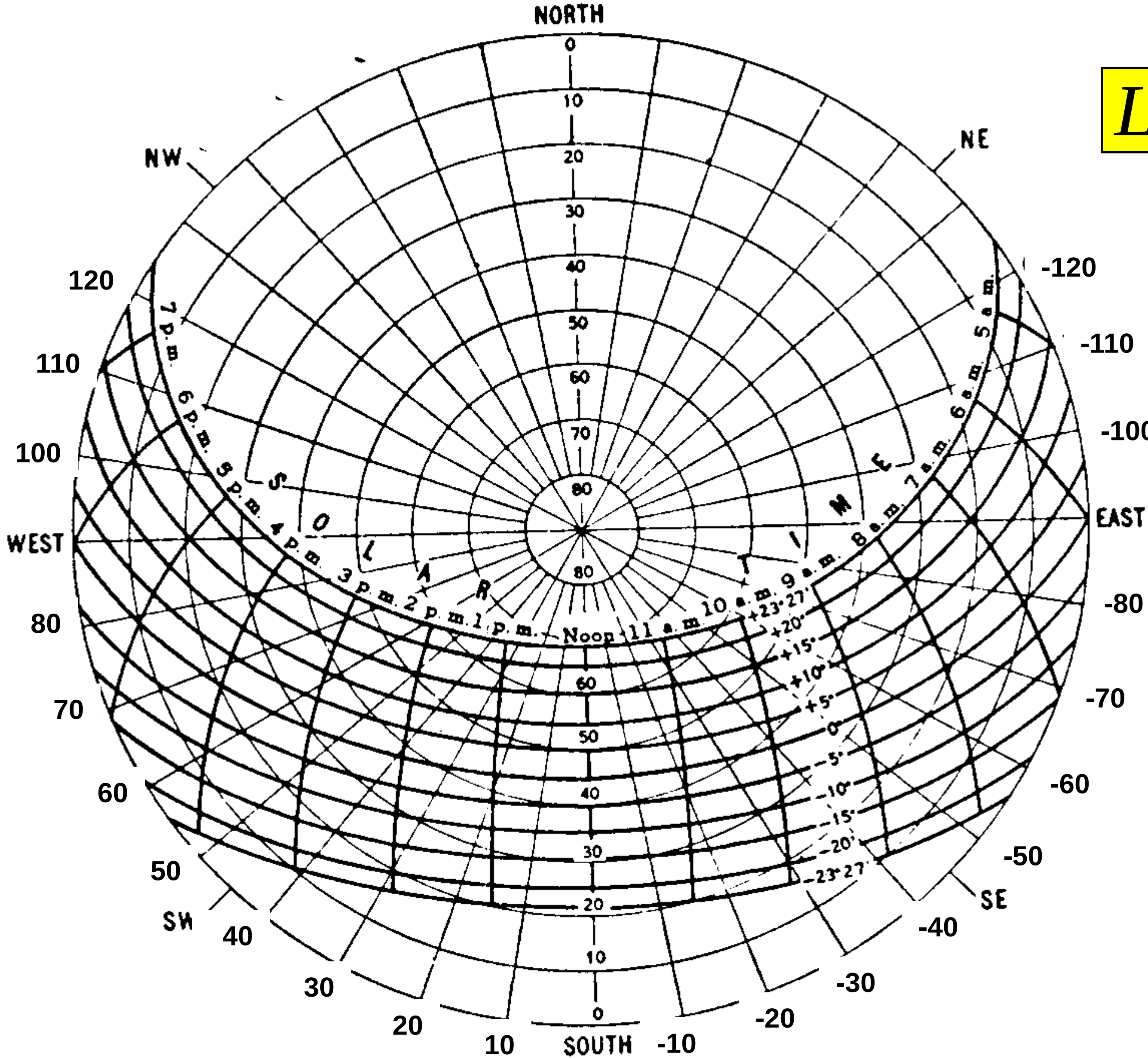
$L = 35°\mathrm{N}$


NORTH
NW
NE
WEST
EAST
SW
SE
SOUTH
120
110
100
80
70
60
50
40
30
20
10
-10
-20
-30
-40
-50
-60
-70
-80
-100
-110
-120
0
10
20
30
40
50
60
70
80
7 p.m.
6 p.m.
5 p.m.
4 p.m.
3 p.m.
2 p.m.
1 p.m.
Noon
11 a.m.
10 a.m.
9 a.m.
8 a.m.
7 a.m.
6 a.m.
5 a.m.
SOLAR TIME
+23°27'
+20°
+15°
+10°
+5°
0°
-5°
-10°
-15°
-20°
-23°27'

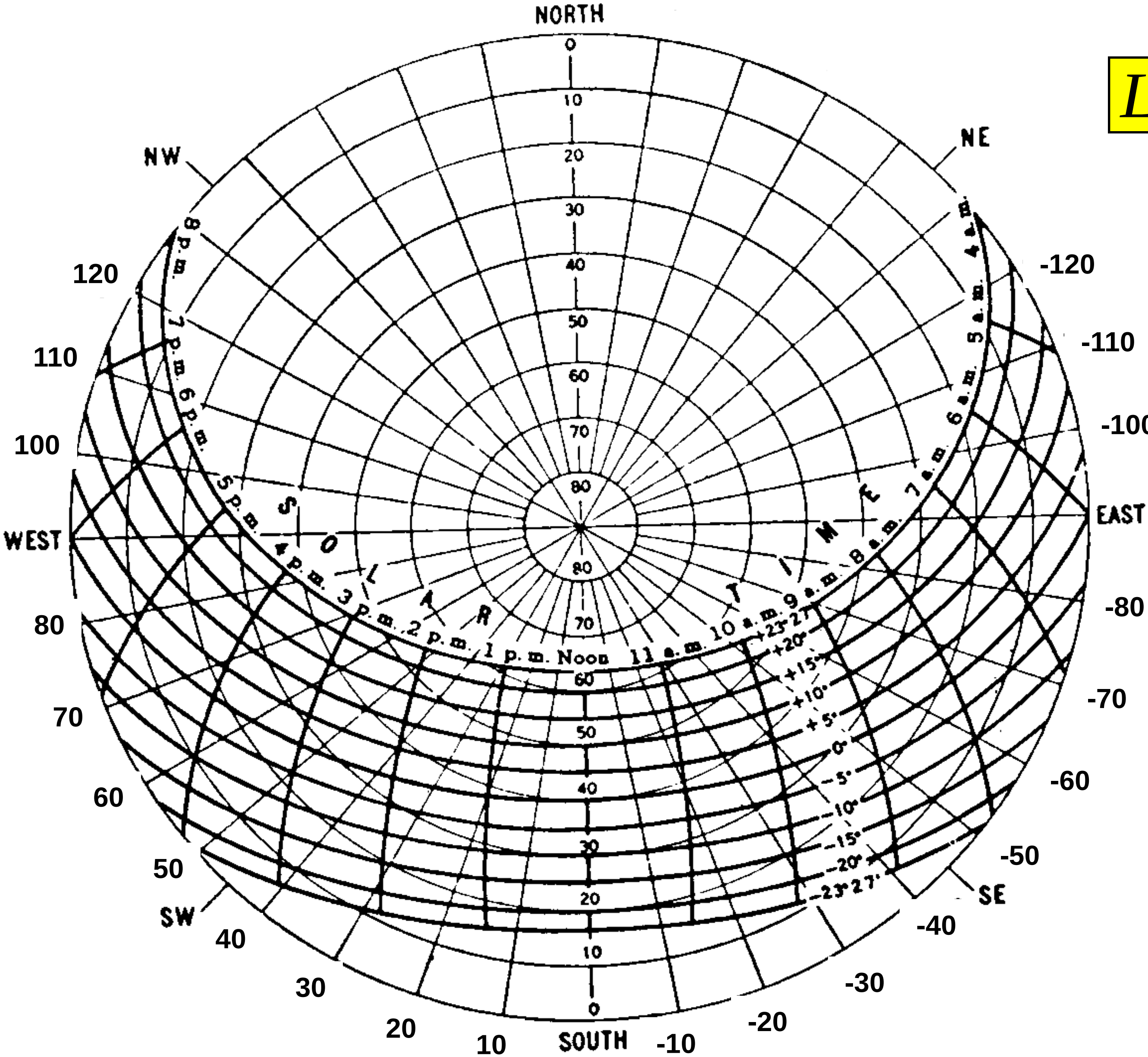


$L = 40°N$
NORTH
NW
NE
WEST
EAST
SW
SE
SOUTH
SOLAR TIME
7 p.m.
6 p.m.
5 p.m.
4 p.m.
3 p.m.
2 p.m.
1 p.m.
Noon
11 a.m.
10 a.m.
9 a.m.
8 a.m.
7 a.m.
6 a.m.
5 a.m.
+23°27'
+20°
+15°
+10°
+5°
0°
−5°
−10°
−15°
−20°
−23°27'
120
110
100
80
70
60
50
40
30
20
10
-10
-20
-30
-40
-50
-60
-70
-80
-100
-110
-120

$L = 45°$


NORTH
NE
EAST
SE
SOUTH
SW
WEST
NW
0
10
20
30
40
50
60
70
80
SOLAR TIME
5 a.m.
6 a.m.
7 a.m.
8 a.m.
9 a.m.
10 a.m.
11 a.m.
Noon
1 p.m.
2 p.m.
3 p.m.
4 p.m.
5 p.m.
6 p.m.
7 p.m.
+23°27'
+20°
+15°
+10°
+5°
0°
-5°
-10°
-15°
-20°
-23°27'
120
110
100
80
70
60
50
40
30
20
10
-10
-20
-30
-40
-50
-60
-70
-80
-100
-110
-120

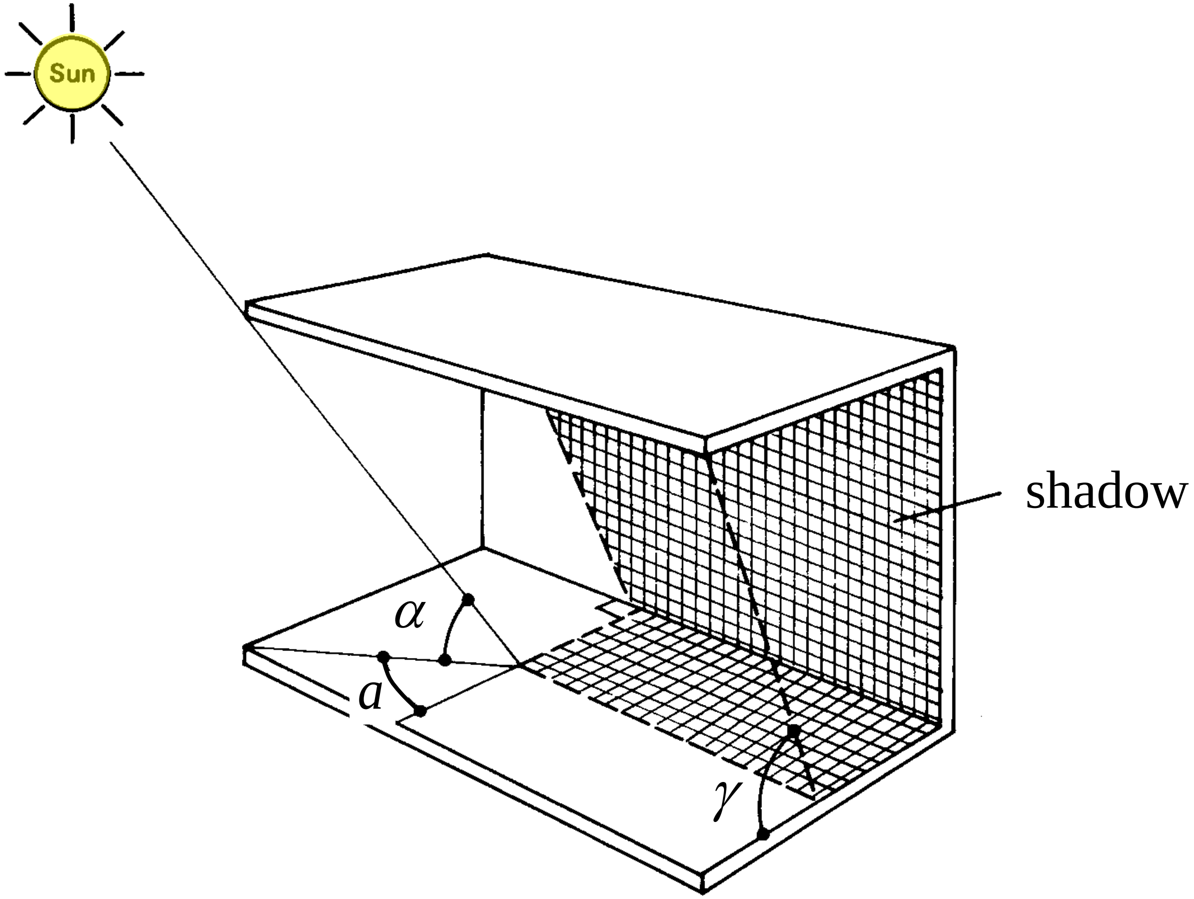
$L = 50°$



NORTH
NE
EAST
SE
SOUTH
SW
WEST
NW
0
10
20
30
40
50
60
70
80
120
110
100
80
70
60
50
40
30
20
10
-10
-20
-30
-40
-50
-60
-70
-80
-100
-110
-120
SOLAR TIME
4 a.m.
5 a.m.
6 a.m.
7 a.m.
8 a.m.
9 a.m.
10 a.m.
11 a.m.
Noon
1 p.m.
2 p.m.
3 p.m.
4 p.m.
5 p.m.
6 p.m.
7 p.m.
8 p.m.
+23°27'
+20°
+15°
+10°
+5°
0°
-5°
-10°
-15°
-20°
-23°27'

Projection of the solar altitude angle α on a given plane, as a function of the angle a

$$\boxed{\tan\gamma = \frac{\tan\alpha}{\cos a}} \qquad (3)$$



Example

Determine the position of the Sun in Frankfurt am Main, Germany (coordinates 50.10ºN, 8.68ºE) on 17th April, at 3p.m. (local solar time).

From the table: 17 April $\rightarrow$ δ_s = + 10º12' = + 10.20º

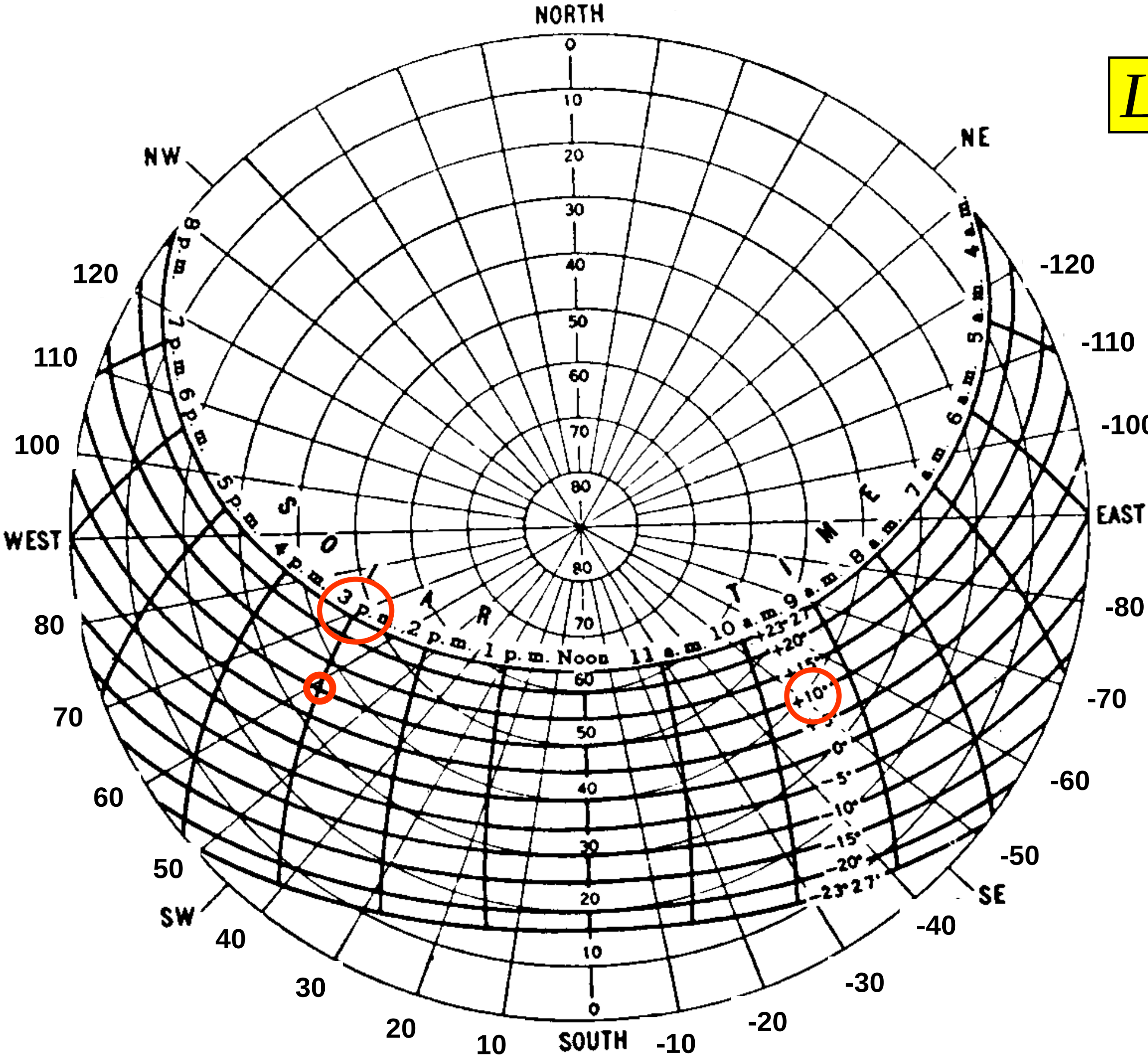
3p.m. $\rightarrow$ $h_s = 3 \times 15° = 45°$

L = 50.10º

From Eqs. (1) and (2), we obtain: $\alpha = 35.6°, \quad a_s = 58.9°$

This agrees well with the values from the graph (see following slide).

$L = 50°$



NORTH
NE
EAST
SE
SOUTH
SW
WEST
NW
S O L A R T I M E
8 p.m.
7 p.m.
6 p.m.
5 p.m.
4 p.m.
3 p.m.
2 p.m.
1 p.m.
Noon
11 a.m.
10 a.m.
9 a.m.
8 a.m.
7 a.m.
6 a.m.
5 a.m.
4 a.m.
+23°27'
+20°
+15°
+10°
+5°
0°
-5°
-10°
-15°
-20°
-23°27'
120
110
100
80
70
60
50
40
30
20
10
-10
-20
-30
-40
-50
-60
-70
-80
-100
-110
-120

Solar radiation on a surface with given orientation

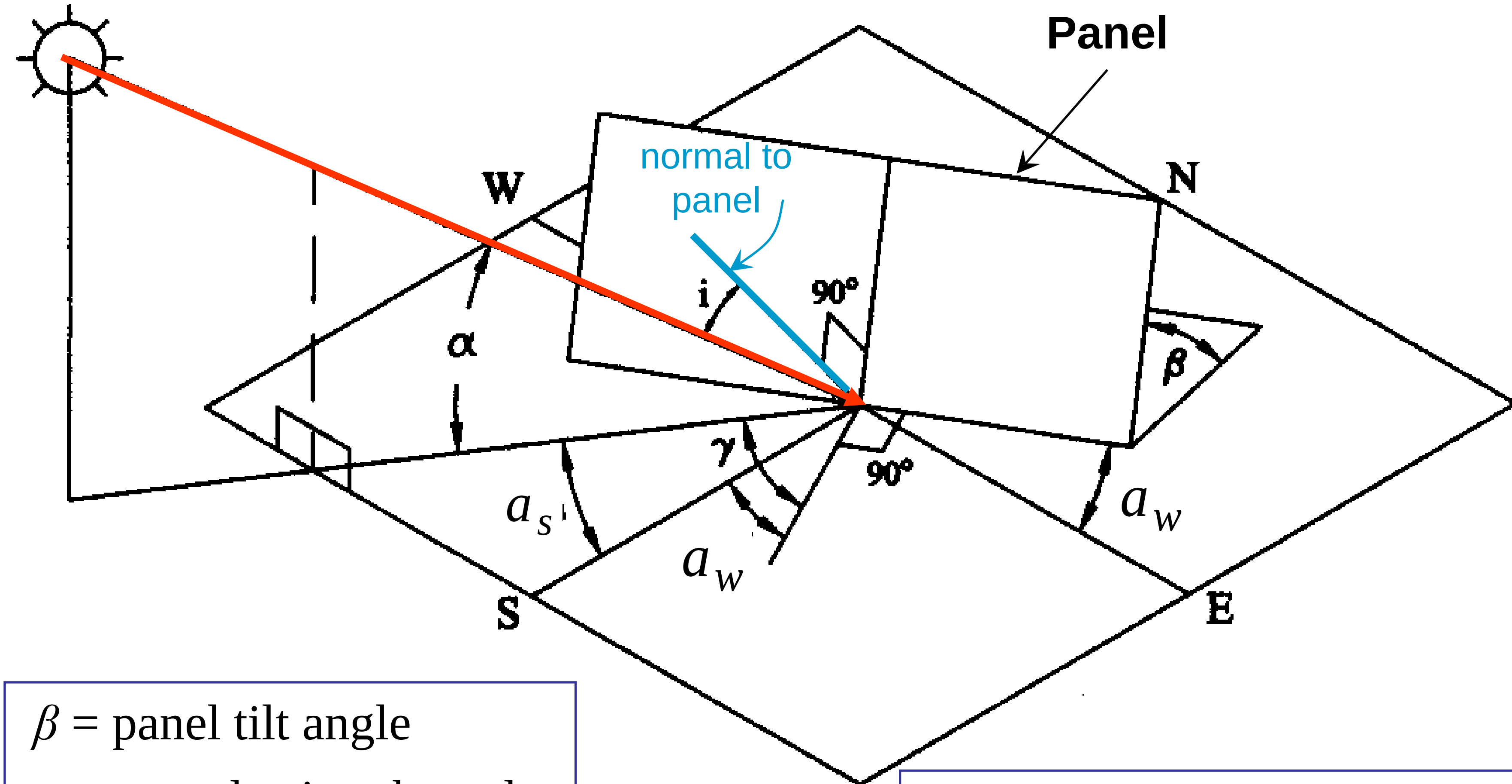
Consider a solar beam with

- solar altitude angle α
- solar azimutn angle a_s
- radiation intensity (referred to a normal surface) I_N (W/m^2)

Consider a tilted surface (i.e. a solar panel) that is not normal to the beam, i.e., with angle of incidence $i \neq 0$ (i = angle between sun rays and normal to surface).

The energy flux received by the (non-normal) surface (per unit area) is

$$\boxed{I_c = I_N \cos i}$$



β = panel tilt angle

a_w = panel azimuth angle

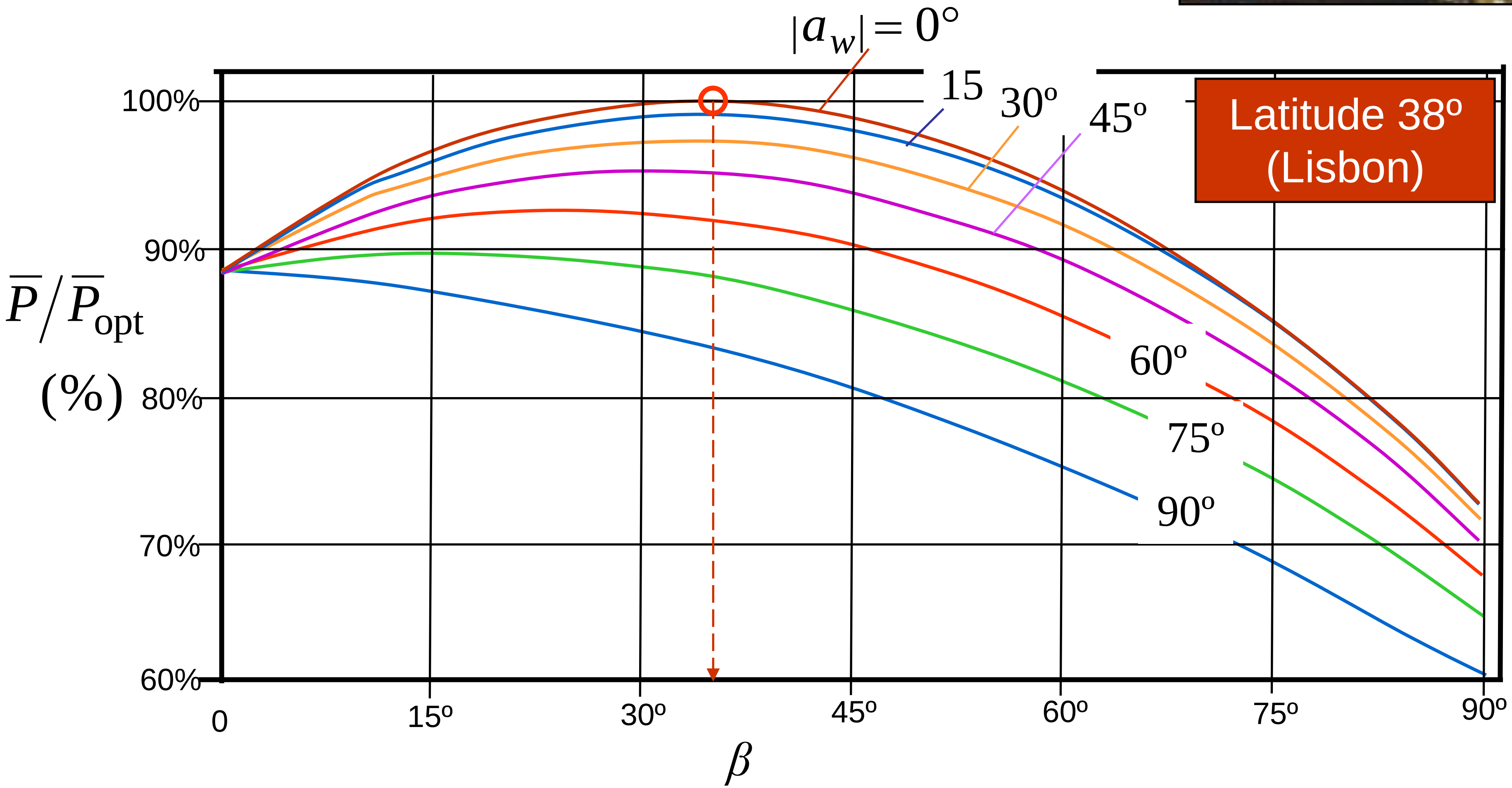
In the figure: $a_s > 0$, $a_w < 0$

$$\cos i = \cos\alpha \cos(a_s - a_w)\sin\beta + \sin\alpha\cos\beta$$

Normal incidence if $a_s = a_w, \ \alpha = 90° - \beta, \quad \therefore \ i = 0$

Fixed panel (thermal or PV):

What is the penalty if it is not optimally oriented (possibly for architectural or practical reasons)?



From: M. Collares Pereira

If the objective is the maximization of collected solar energy, the orientation of a fixed panel should be $a_w = 0$ and $\beta \cong L$ (sometimes $\beta = L - 3°$ is recommended).

The penalty is relatively small if a different (but not too different) orientation is adopted, possibly for practical or architectural reasons (e.g. accommodate a solar panel on an existing roof).

There could be special reasons for choosing $a_w \neq 0$. E.g., $a_w > 0$ allows more energy to be collected in the afternoon, which could be convenient for a thermal panel if the heated water is to be used in the evening.

Exercise

Consider a plane panel (thermal or photovoltaic), with an area equal to $1m^2$, whose orientation is defined by the angles a_w and β. Assume the solar radiation intensity $I_N = 1000\,\mathrm{W/m^2}$.

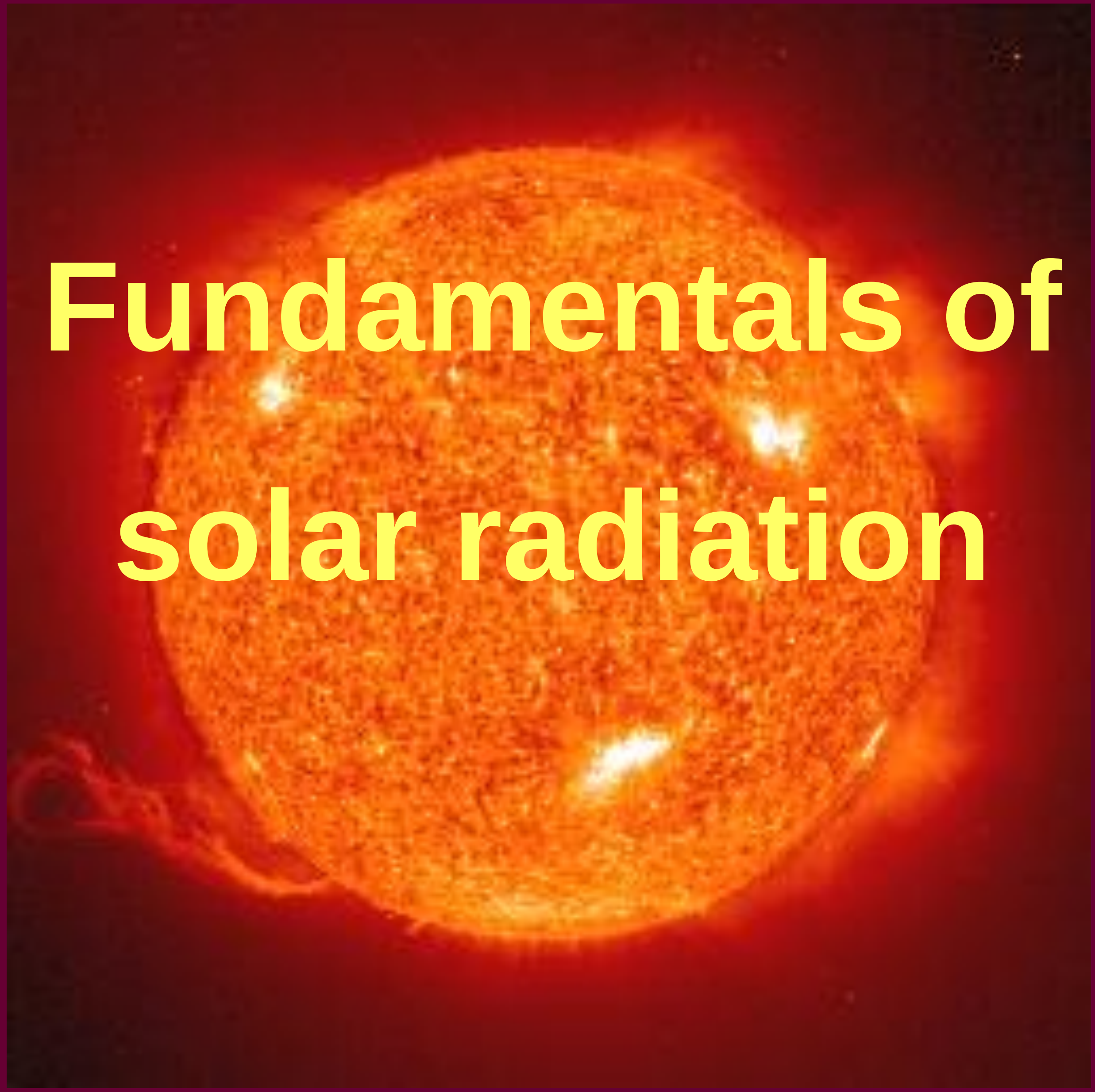
Compute the total amount of solar energy (in J) received by the panel (choose the orientation), located at a given point on Earth (choose where), on given day of the year (choose when), over a given interval of time (number of hours).

In particular, the following data are suggested:

• $a_w = 0$ (the panel faces South); angle β to be optimized; day: Spring or Autumn equinox; period: from 7h00 to 17h00 (solar time). Choose the latitude.

• Determine the angle β that maximizes the amount of received energy.

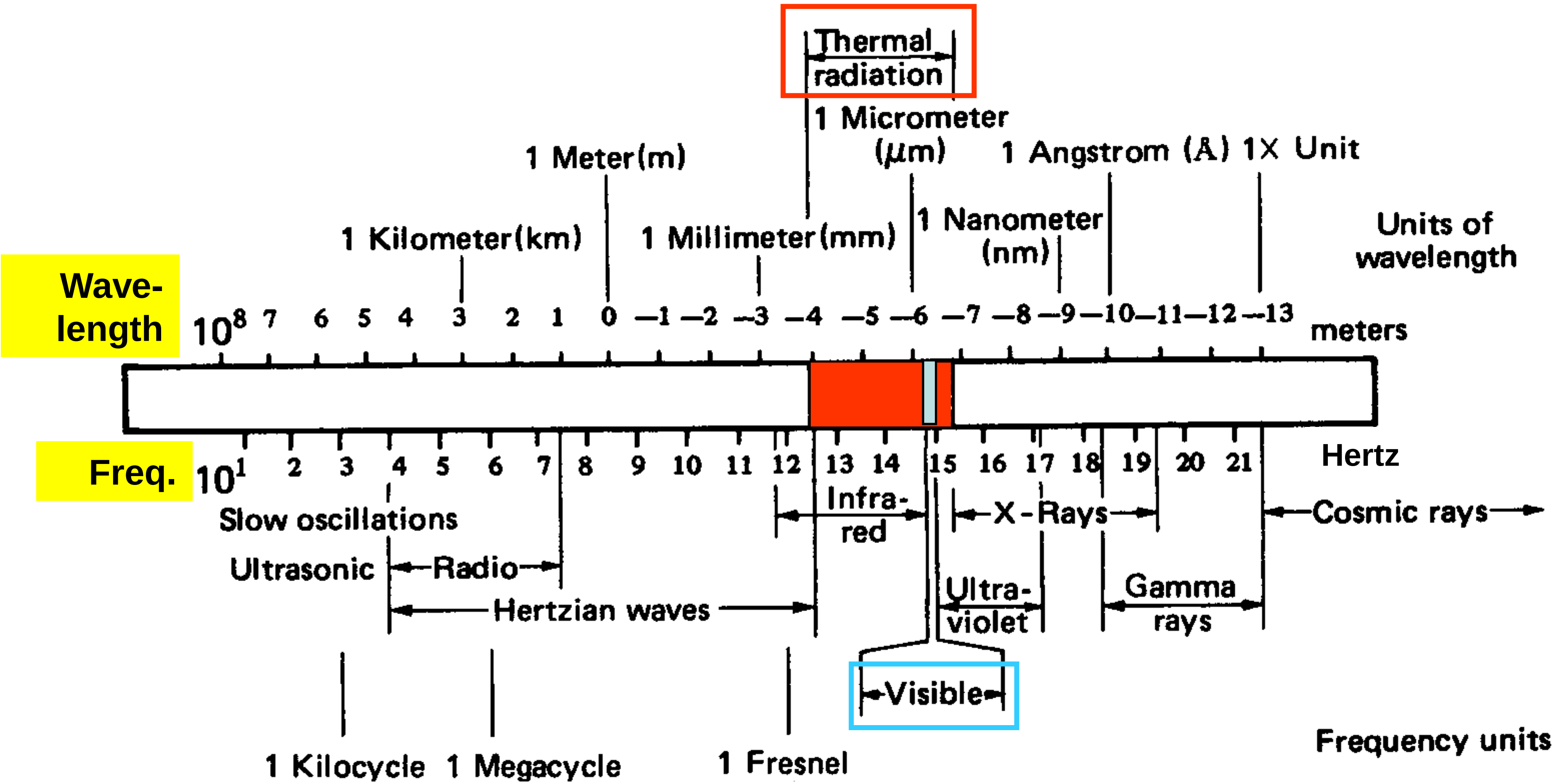
Fundamentals of solar radiation



Thermal radiation is one kind of electromagnetic energy.

All bodies emit thermal radiation by virtue of their temperature.

The radiation emitted by a body is distributed over a range of wavelengths, depending on its temperature.



$$\boxed{c = \lambda f} \quad \begin{cases} c = \text{speed of light} \\ \lambda = \text{wavelength} \\ f = \text{frequency} \end{cases}$$

Black body (corpo negro) is a perfect thermal radiator.

$E_{b\lambda}$ (W/(m^2.μm)) = energy flux density, per unit area and per unit wavelength band.

$$\boxed{\text{For a black body:} \quad E_{b\lambda} = \frac{C_1}{\left(e^{C_2/\lambda T} - 1\right)\lambda^5 n^2}}$$

Planck distribution

$$\begin{cases} C_1 = 3.74 \times 10^8 \ \mathrm{W \cdot \mu m^4 / m^2} \\ C_2 = 1.44 \times 10^4 \ \mathrm{\mu m \cdot K} \\ T = \text{absolute temperatura of black body K} \\ n = \text{refractive index of medium } (=1 \text{ vacuum}; \ \cong 1 \text{ air}) \end{cases}$$

Total energy emitted by a black body:

$$\boxed{E_b = \int_0^\infty E_{b\lambda}\, d\lambda = \sigma T^4}$$ Stefan-Bolzmann law

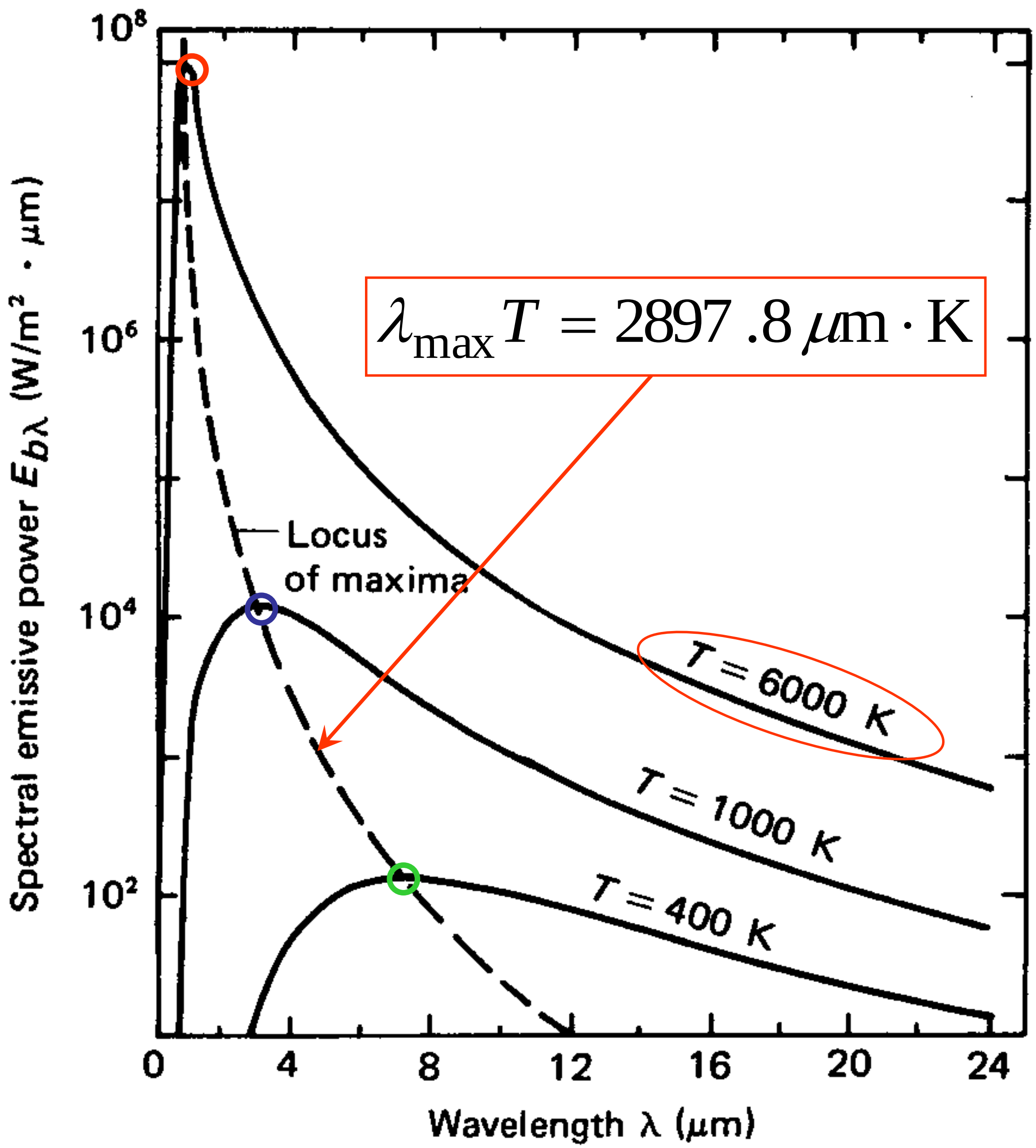
$$\sigma = 5.67\times 10^{-8}\ \mathrm{W}/(\mathrm{m}^2\cdot \mathrm{K}^4)$$ Stefan-Bolzmann constant

The radiated energy increases very fast with body temperature.

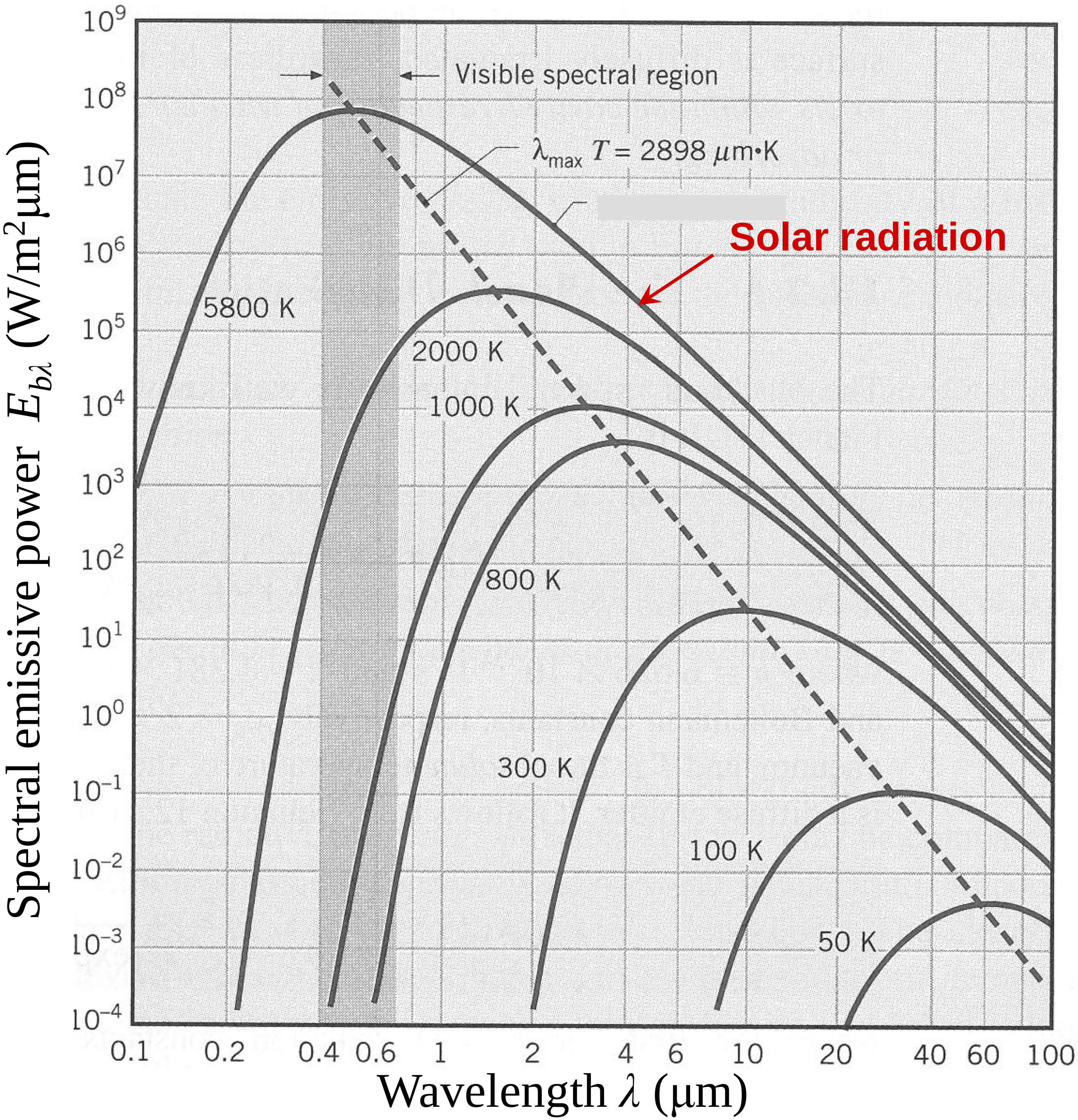
For given temperature *T*, $E_{b\lambda}$ is maximum for $dE_{b\lambda}/d\lambda = 0$, or

$$\boxed{\lambda_{\max} T = 2897.8\ \mu\mathrm{m}\cdot\mathrm{K}}$$

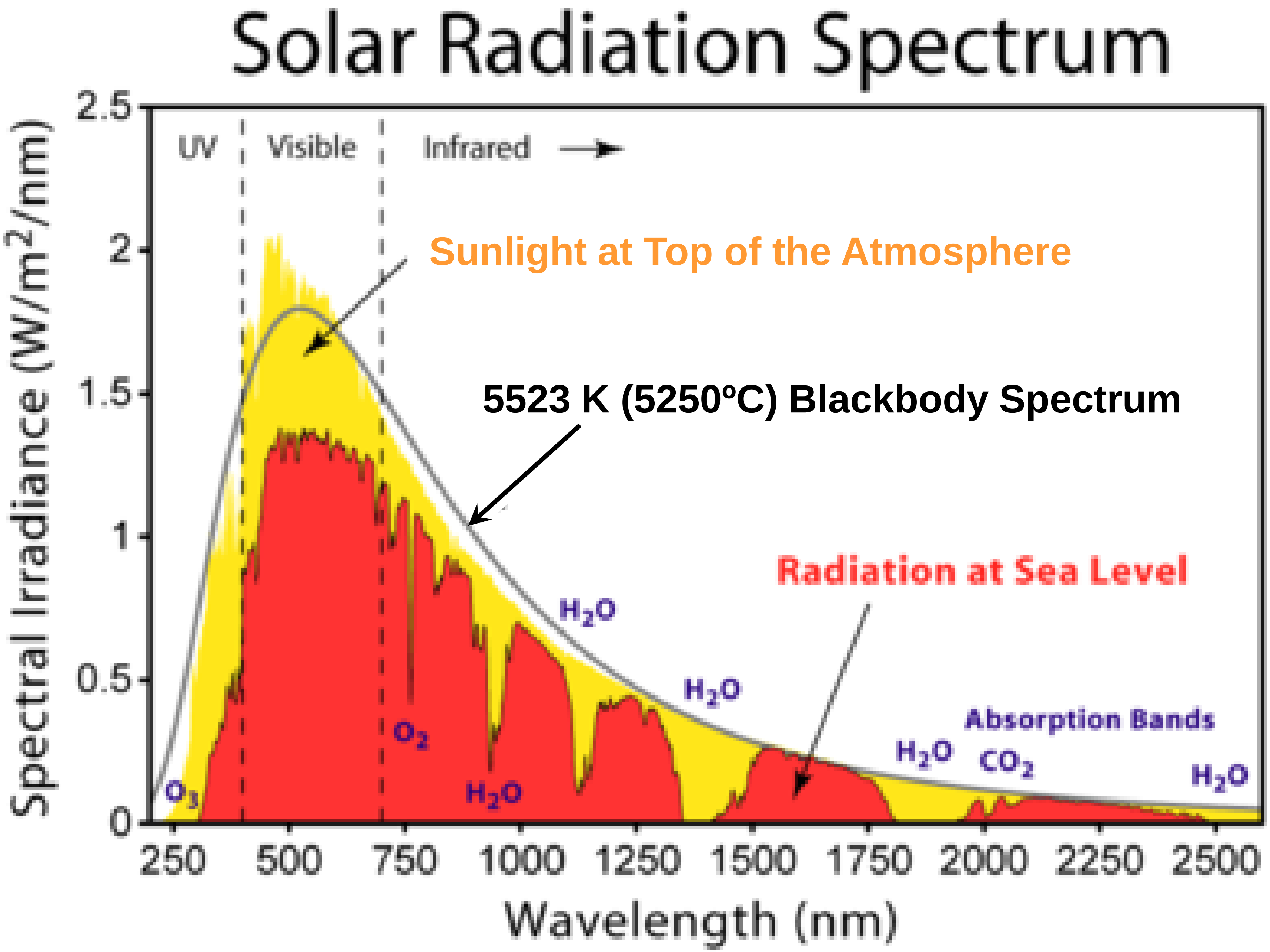
Bodies at higher temperature *T* radiate energy at smaller wavelengths (or at higher frequencies).



$\lambda_{max} T = 2897.8\ \mu m \cdot K$
Locus of maxima
$T = 6000$ K
$T = 1000$ K
$T = 400$ K
10^8
10^6
10^4
10^2
0
4
8
12
16
20
24
Spectral emissive power $E_{b\lambda}$ (W/m^2 · μm)
Wavelength λ (μm)



Visible spectral region
$\lambda_{max} T = 2898\ \mu m \cdot K$
Solar radiation
5800 K
2000 K
1000 K
800 K
300 K
100 K
50 K
Spectral emissive power $E_{b\lambda}$ (W/m^{2}μm)
Wavelength λ (μm)
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.1 0.2 0.4 0.6 1 2 4 6 10 20 40 60 100


Solar Radiation Spectrum
Spectral Irradiance (W/m²/nm)
Wavelength (nm)
UV
Visible
Infrared
Sunlight at Top of the Atmosphere
5523 K (5250ºC) Blackbody Spectrum
Radiation at Sea Level
Absorption Bands
O_3
O_2
H_2O
CO_2
0
0.5
1
1.5
2
2.5
250
500
750
1000
1250
1500
1750
2000
2250
2500

Solar radiation above the Earth atmosphere

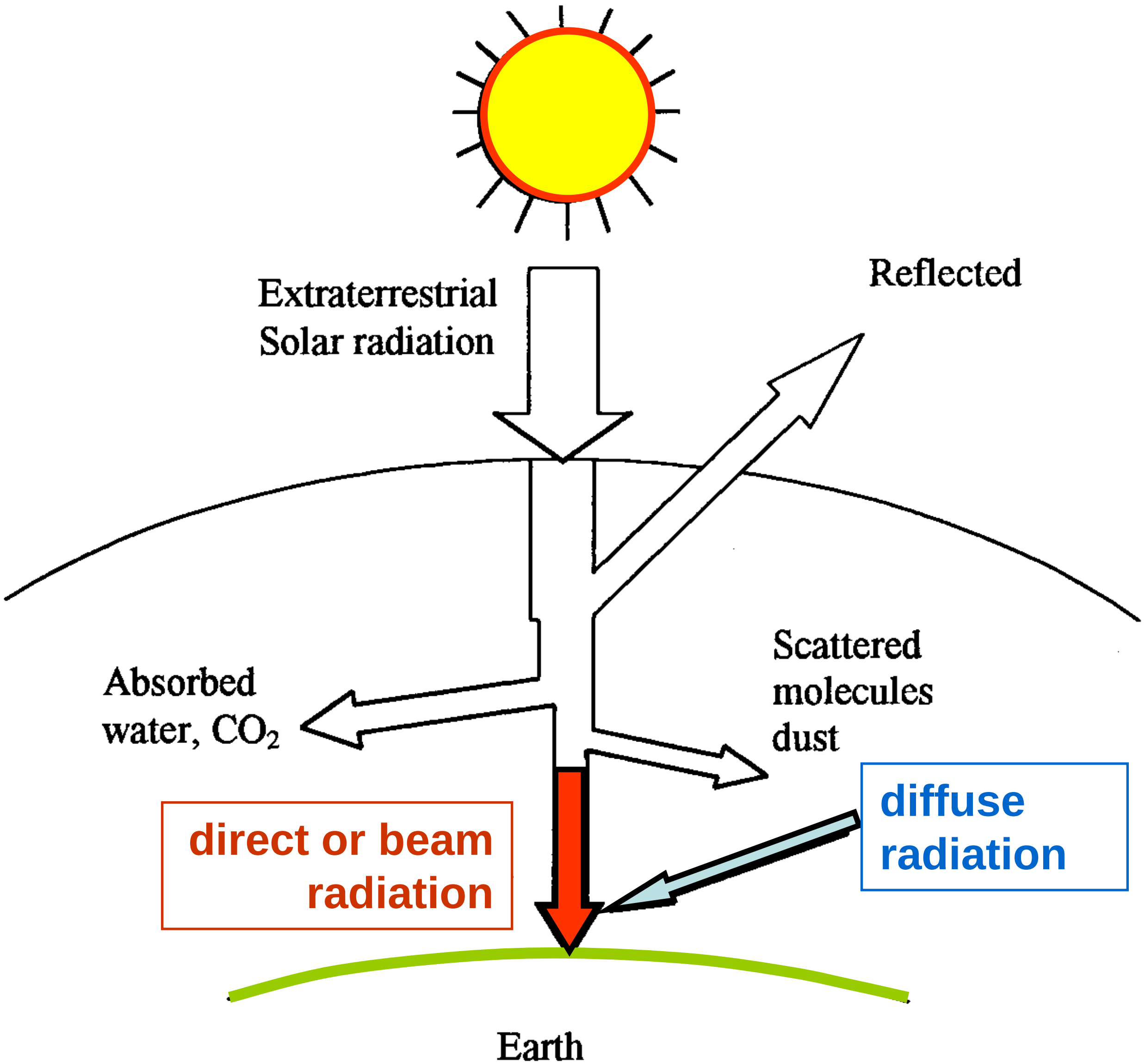
The intensity of solar radiation above the atmosphere depends on the the distance to the Sun (which varies slightly along the year).

In average it is approximately $I_0 = 1367\ \mathrm{W/m^2} = \text{solar constant.}$

The following expression takes into account that the distance to the Sun varies as the Earth moves along the ecliptic:

$$\boxed{I = I_0 \left[1 + 0.034 \cos(360\,(n-2)/365.25)^\circ\right]}$$

where n = day number (starting at n = 1 on January 1st).


Extraterrestrial
Solar radiation
Reflected
Absorbed
water, CO_2
Scattered
molecules
dust
direct or beam
radiation
diffuse
radiation
Earth

Atmospheric extinction of solar radiation

As solar radiation travels through the atmosphere, it is attenuated due to absorption and scattering.

Let $K(x)$ be the local extinction coefficient of the atmosphere (at given altitude x). The attenuation factor for vertical radiation (α = 90º) is

$$\int_0^{L_0} K(x)\,dx = k \qquad (L_0 = \text{vertical thickness of atmosphere})$$

For non-vertical radiation (α < 90º), the path is longer, and k should be replaced by $k/\sin\alpha$. $\quad 1/\sin\alpha = m = \text{air mass ratio}$

The **beam solar radiation** **(radiação directa)** (on a normal surface) at the Earth's surface is

$$\boxed{I_{b,N} = I\,e^{-k/\sin\alpha}}$$

On a clear day and vertical sun rays (α = 90º), the solar radiation on the surface of the Earth is approximately I = 1000 W/m^2.

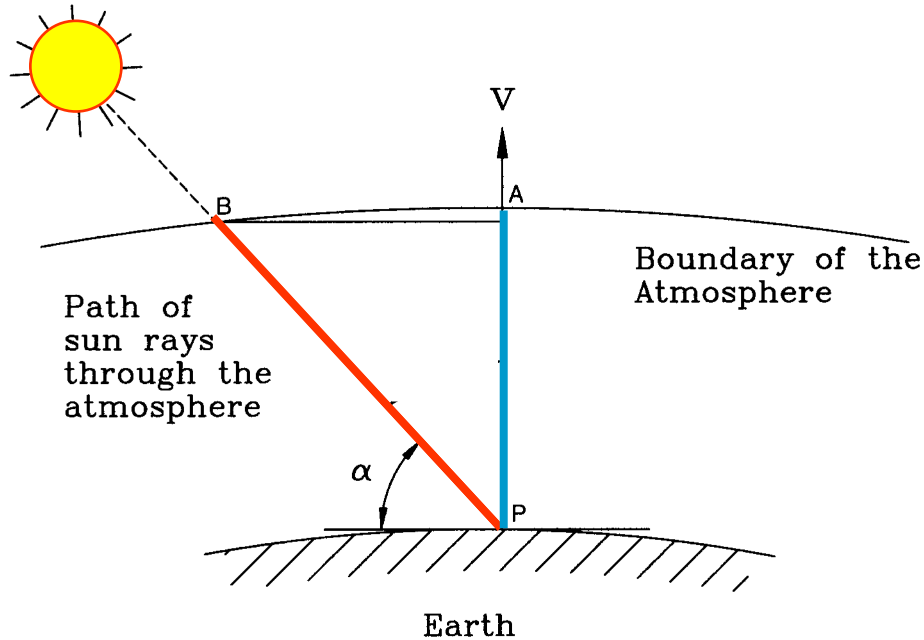
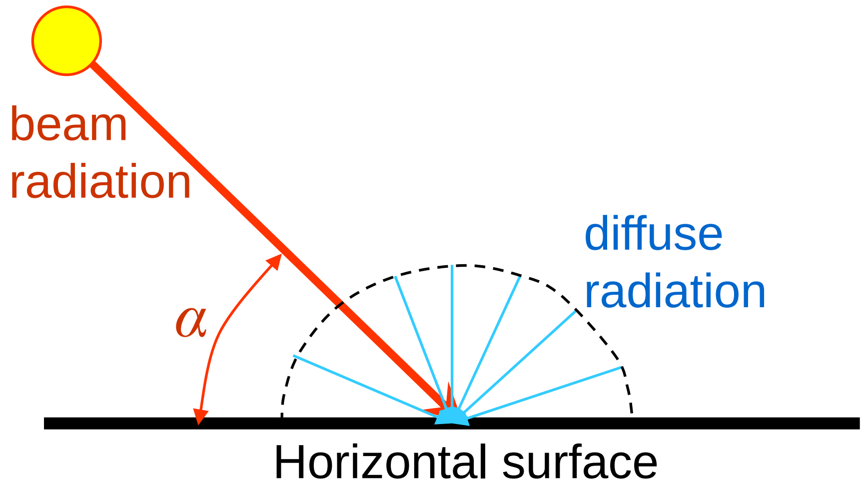


Table 2.4. Average values of atmospheric optical depth (*k*) and sky diffuse factor (*C*) for 21st day of each month, for average atmospheric conditions at sea level for the United States

Month	1	2	3	4	5	6	7	8	9	10	11	12
k	0.142	0.144	0.156	0.180	0.196	0.205	0.207	0.201	0.177	0.160	0.149	0.142
C	0.058	0.060	0.071	0.097	0.121	0.134	0.136	0.122	0.092	0.073	0.063	0.057

Beam solar radiation + sky diffuse radiation



On a horizontal surface: $$I_h = I_{b,h} + I_{d,h} = \underbrace{\boxed{I_{b,N}\sin\alpha}}_{\text{beam or direct}} + \underbrace{\boxed{CI_{b,N}}}_{\text{diffuse}}$$

On a tilted surface (panel): $$I_{\text{panel}} = \boxed{I_{b,N}\cos i} + \boxed{CI_{b,N}\cos^2(\beta/2)}$$

$\boxed{\text{Note: } \cos^2(\beta/2) = \text{part of sky "viewed" by the panel}}$

Estimativas das médias mensais e anual do número de horas de sol descoberto, em diversos locais da Europa, para o período 1981-90 (ordenação por valores anuais crescentes).

LOCAL	JAN	FEV	MAR	ABR	MAI	JUN	JUL	AGO	SET	OUT	NOV	DEZ	ANUAL
DUBLIN	59	68	105	153	186	162	177	143	129	96	66	47	1390
HAMBURGO	40	79	96	167	226	180	211	208	132	99	60	31	1530
LONDRES	62	79	105	174	192	180	211	205	141	112	72	43	1576
PRAGA	43	82	121	177	217	180	229	214	150	124	48	37	1622
HELSINQUÍA	37	79	118	202	273	264	273	195	120	84	36	25	1705
MUNIQUE	68	93	124	164	205	192	245	217	165	127	75	50	1725
PARIS	59	99	124	183	205	201	251	226	165	121	87	50	1770
KIEV	50	71	124	177	273	261	282	273	174	133	54	40	1911
GÉNOVA	124	130	164	180	205	249	304	270	201	164	120	112	2222
ATENAS	146	138	189	233	282	333	353	332	279	211	141	127	2764
CASABLANCA	198	186	248	258	304	285	291	285	246	236	192	198	2928
SEVILHA	169	151	238	235	313	348	350	322	243	192	217	154	2931

Fonte: M. Collares Pereira

Estimativas das médias mensais e anual do número de horas de sol descoberto, em diversos locais de Portugal, para o período 1981-90 (ordenação por valores anuais crescentes).

Local	Jan	Fev	Mar	Abr	Mai	Jun	Jul	Ago	Set	Out	Nov	Dez	Anual
Mar.Grande	116	131	147	195	246	238	257	242	203	180	127	110	2191
Vila Real	94	118	155	197	239	271	335	308	214	174	124	89	2319
Viseu	117	131	163	195	242	270	322	300	219	184	139	129	2411
Coimbra	131	141	173	213	252	259	302	289	221	186	148	136	2450
Porto	120	132	173	229	260	273	313	286	219	186	143	123	2458
Bragança	106	134	172	218	262	297	362	331	231	183	138	101	2534
Santarém	113	139	178	229	270	297	343	324	236	192	134	117	2573
Lisboa	125	141	176	224	273	285	334	317	237	190	149	131	2581
Portalegre	127	139	171	212	266	289	354	335	228	188	153	142	2603
Beja	139	146	175	224	277	295	350	329	241	193	153	141	2662
Évora	140	147	181	228	282	302	361	341	247	201	156	145	2732
Faro	158	161	217	253	308	327	364	352	266	214	183	171	2974
Pta.Delgada	89	95	120	136	170	164	198	208	173	140	99	88	1681
Funchal	141	145	183	188	204	174	229	237	207	183	148	144	2184

Fonte: M. Collares Pereira

Estimativas das médias mensais e anual da irradiação solar global horizontal dária (MJ/m²) em diversos locais da Europa, para o período 1981-90 (ordenação por valores anuais crescentes).

Local	Jan	Fev	Mar	Abr	Mai	Jun	Jul	Ago	Set	Out	Nov	Dez	Anual
Helsinquía	0.86	3.20	7.07	13.26	18.97	20.18	19.55	13.47	7.79	3.59	1.13	0.42	9.12
Londres	2.46	4.40	7.63	12.82	15.46	16.13	16.46	14.48	9.79	5.82	3.07	1.75	9.19
Dublin	2.33	4.09	8.02	12.95	16.69	17.12	17.04	13.16	9.95	5.66	2.83	1.67	9.29
Hamburgo	1.89	4.33	7.25	13.19	18.32	17.19	17.85	15.20	9.82	5.50	2.55	1.36	9.54
Praga	2.69	4.66	8.44	13.21	16.99	16.94	18.00	15.24	9.70	6.43	2.61	1.75	9.72
Paris	2.93	5.85	10.24	14.22	17.29	18.70	19.99	16.62	11.79	7.62	4.23	2.36	10.99
Munique	3.47	6.45	9.83	14.20	18.11	18.55	19.84	16.78	12.13	7.59	4.11	2.68	11.15
Kiev	3.15	5.93	10.17	14.53	21.47	21.01	20.37	18.12	12.09	7.69	3.47	2.36	11.70
Génova	5.00	7.43	11.49	14.95	18.01	21.58	22.38	19.47	14.27	9.19	5.60	4.10	12.79
Madrid	7.39	9.50	16.18	18.28	23.68	26.76	26.64	23.32	18.07	12.01	7.85	5.77	16.29
Atenas	8.03	10.37	15.17	19.48	22.99	26.69	26.50	23.65	19.28	13.33	8.58	7.05	16.76
Sevilha	9.08	11.22	17.09	19.95	25.02	27.86	27.03	24.32	18.51	13.09	11.46	7.97	17.72
Casablanca	11.17	13.73	18.44	21.74	24.93	24.80	24.35	23.04	19.46	15.85	11.76	10.45	18.31

Fonte: M. Collares Pereira

Estimativas das médias mensais e anual da irradiação solar global horizontal dária (MJ/m^2) em diversos locais da Portugal, para o período 1981-90 (ordenação por valores anuais crescentes).

LOCAL	JAN	FEV	MAR	ABR	MAI	JUN	JUL	AGO	SET	OUT	NOV	DEZ	ANUAL
VILA REAL	5.67	8.63	12.14	16.77	20.10	22.66	24.95	22.16	15.74	11.00	7.11	5.00	14.33
MAR.GRANDE	6.65	9.60	12.26	17.32	21.26	21.76	22.07	20.01	16.06	11.93	7.66	5.93	14.37
VISEU	6.04	8.89	12.13	16.43	20.19	22.96	25.32	22.76	16.22	11.42	7.46	5.94	14.65
PORTO	6.27	9.03	12.75	18.20	21.01	22.74	23.96	21.22	15.95	11.40	7.60	5.80	14.66
COIMBRA	6.65	9.44	12.74	17.56	20.87	22.28	24.10	22.16	16.47	11.64	7.93	6.29	14.85
BRAGANÇA	5.86	9.09	12.75	17.66	21.11	23.92	26.15	23.15	16.38	11.20	7.40	5.21	14.99
SANTARÉM	6.68	10.07	13.84	19.35	22.71	25.31	27.01	24.63	17.92	12.58	8.03	6.25	16.20
PORTALEGRE	7.33	10.31	13.79	18.52	22.42	24.62	26.97	24.59	17.43	12.47	8.82	7.15	16.20
LISBOA	7.20	10.31	13.84	19.15	22.96	24.68	26.54	24.31	18.07	12.61	8.73	6.84	16.27
BEJA	8.01	10.87	14.19	19.32	23.14	25.06	26.96	24.52	18.27	12.98	9.18	7.44	16.66
ÉVORA	7.90	10.79	14.35	19.42	23.31	25.37	27.45	25.03	18.44	13.17	9.13	7.41	16.81
FARO	7.74	10.32	14.75	19.41	23.56	25.87	27.33	25.62	18.78	12.91	9.51	7.76	16.96
PTA.DELGADA	7.10	8.21	11.54	16.56	17.48	18.27	18.54	18.21	14.45	10.62	8.07	6.44	12.96
FUNCHAL	9.99	12.51	16.65	20.07	22.77	22.23	23.31	22.23	18.63	14.67	10.53	9.27	16.91

Fonte: M. Collares Pereira

JOINT RESEARCH CENTRE
OF THE EUROPEAN COMMISSION

Solar interactive data for Europe (site-by-site) available at:

http://re.jrc.ec.europa.eu/pvgis/apps/radmonth.php?lang=en&map=europe

Solar Energy Technology

Thermal radiation and the glass – the greenhouse effect

The most important solar property of **glass** is that:

• it is almost perfectly **transparent** to solar radiation (including visible light),

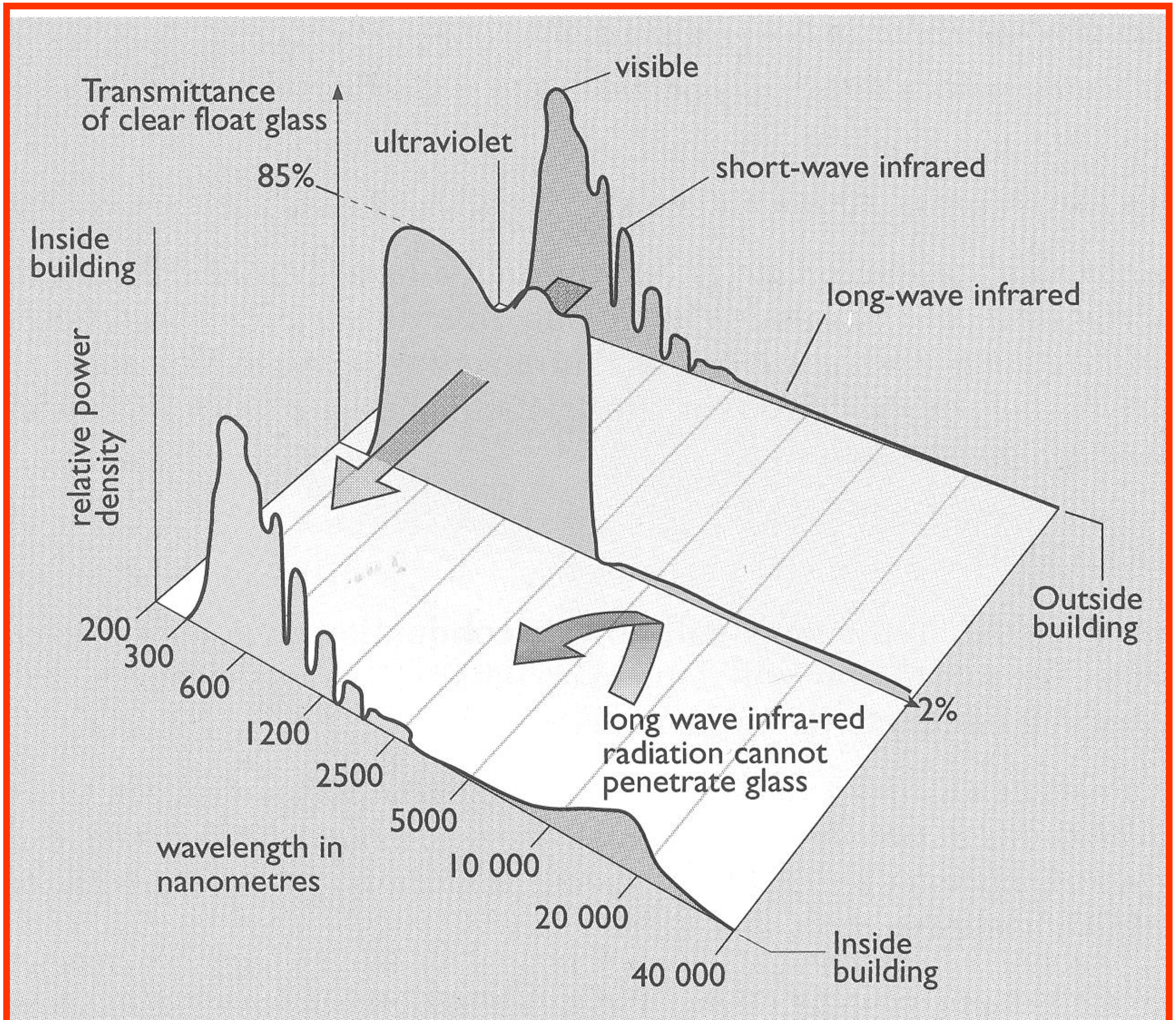
• but almost **opaque** to long-wave infrared radiation emitted by low temperature bodies.

The transparency or transmittance (visible radiation) improves by minimizing the iron content of the glass.

Some plastics have optical properties similar to glass and can be used instead.

This effect is used in thermal solar panels, in passive heating of houses, and in greenhouses (estufas).

Spectral transmission of glass



Optical properties of commonly used glazing materials

Material	Thickness (mm)	Solar transmittance	Long-wave infrared transmittance
Float glass (normal window glass)	3.9	0.83	0.02
Low-iron glass	3.2	0.90	0.02
Perspex	3.1	0.82	0.02
Polyvinyl floride film (Tedlar)	0.1	0.92	0.22
Polyester film (Mylar)	0.1	0.87	0.18

Solar Thermal Energy

ENERGIA SOLAR TÉRMICA

Aquecimento solar activo de "baixas" temperaturas

• Com uso de colectores solares (em geral planos) (no telhado, etc.)
• "Baixas" temperaturas (< 100°C).
• Aplicações: águas domésticas, piscinas, etc.

Aquecimento solar activo de "altas" temperaturas

• Accionamento de máquinas térmicas (turbinas de vapor) para produção de energia eléctrica.
• 90% concentrado na central do deserto de Mohave (Califórnia) .

Aquecimento solar passivo

• Aquecimento de espaços habitados.
• Normalmente com circulação de ar (convecção natural).

Em geral tecnologias bem conhecidas.

Exigem bom conhecimento do clima local.

Não podem ser directamente transpostas entre climas muito diferentes.

SOLAR TÉRMICO ACTIVO

Colectores solares planos

Aquecimento de águas:

- **domésticas** (> 80% do mercado)
- equipamentos sociais: hospitais, hotéis, etc.
- piscinas (menor ΔT)
- processos industriais

Alternativas ao solar térmico activo para águas domésticas:

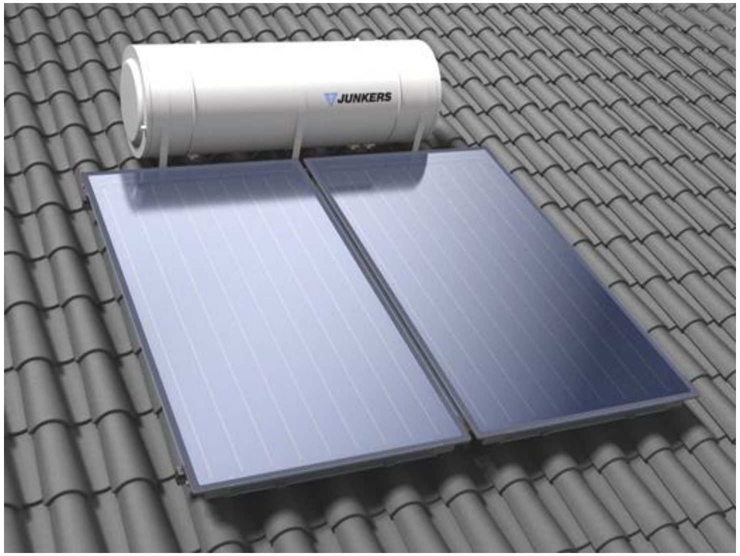
- Acumulador (cilindro) com aquecimento:
  - eléctrico
  - a gás
- Esquentador de água corrente (em geral a gás)

Redução das emissões de CO_2 pelo uso de energia solar

(em kg CO_2/kWh de calor produzido):

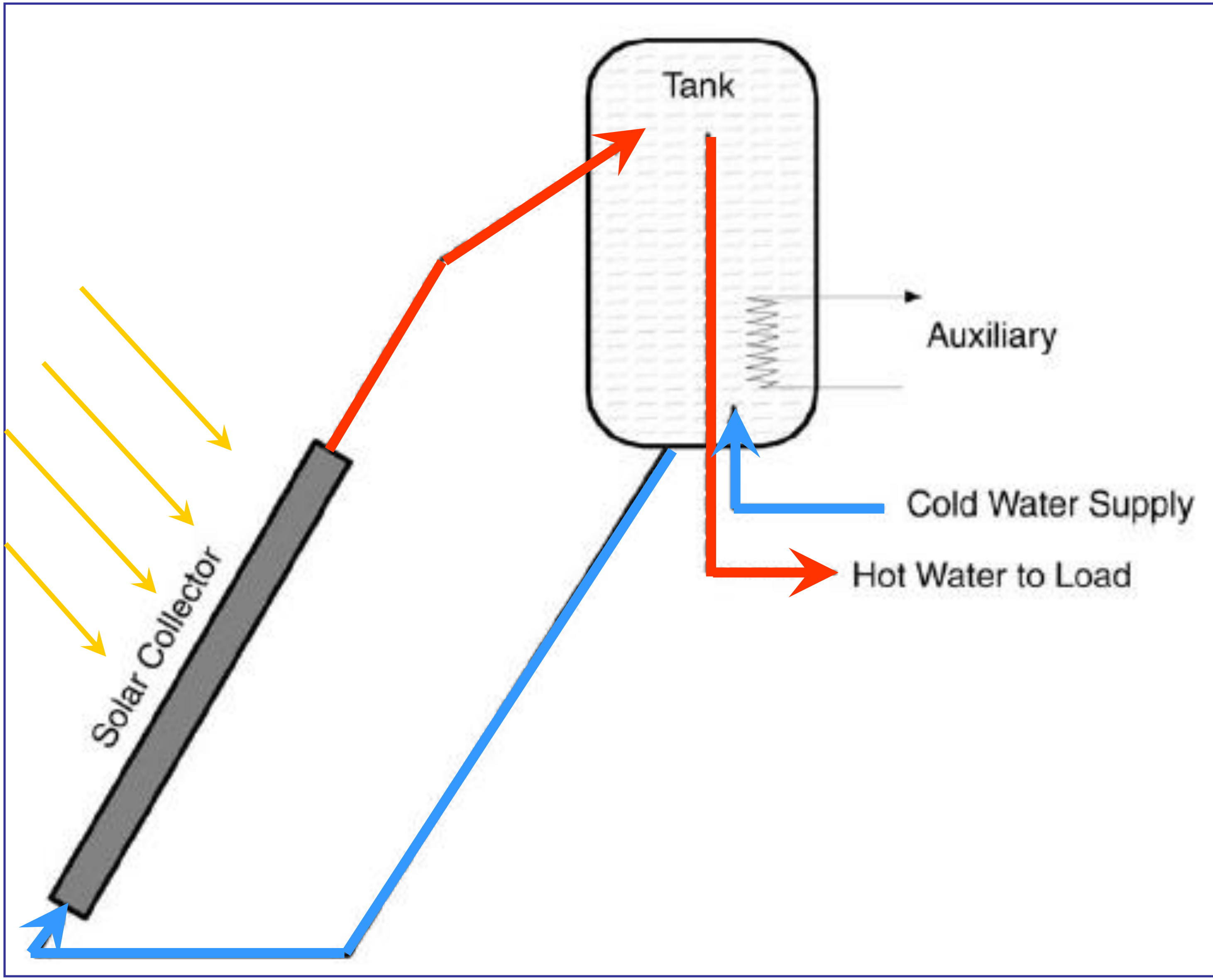
- 1 kg CO_2/kWh, se evita o aquecimento eléctrico (electricidade de "origem fóssil")
- 0,2 kg CO_2/kWh, se evita o aquecimento a gás

(Fonte: M. Collares Pereira, Energias renováveis: a opção inadiável)

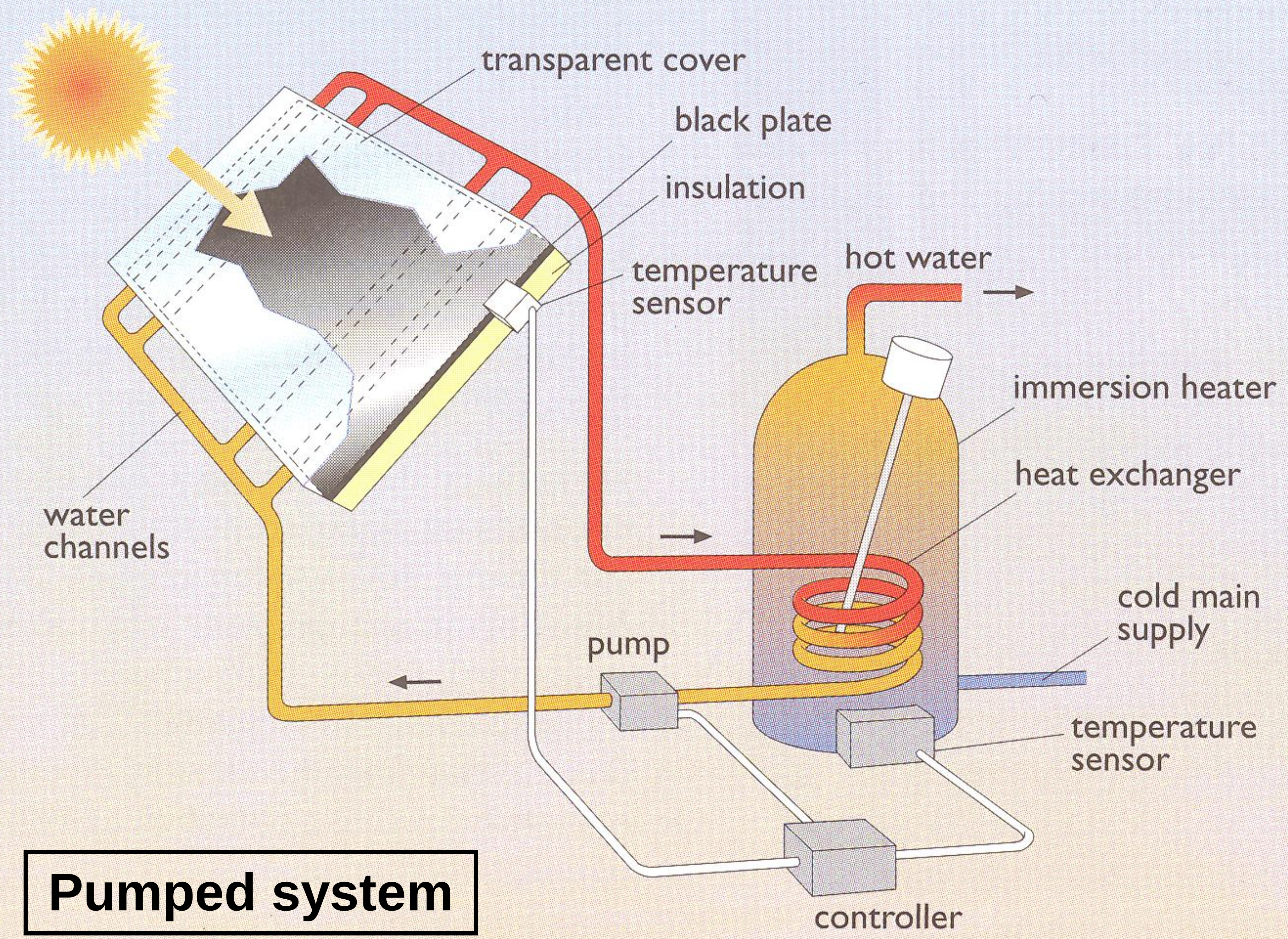


Monobloc (thermosiphon) passive system

Pumped active system

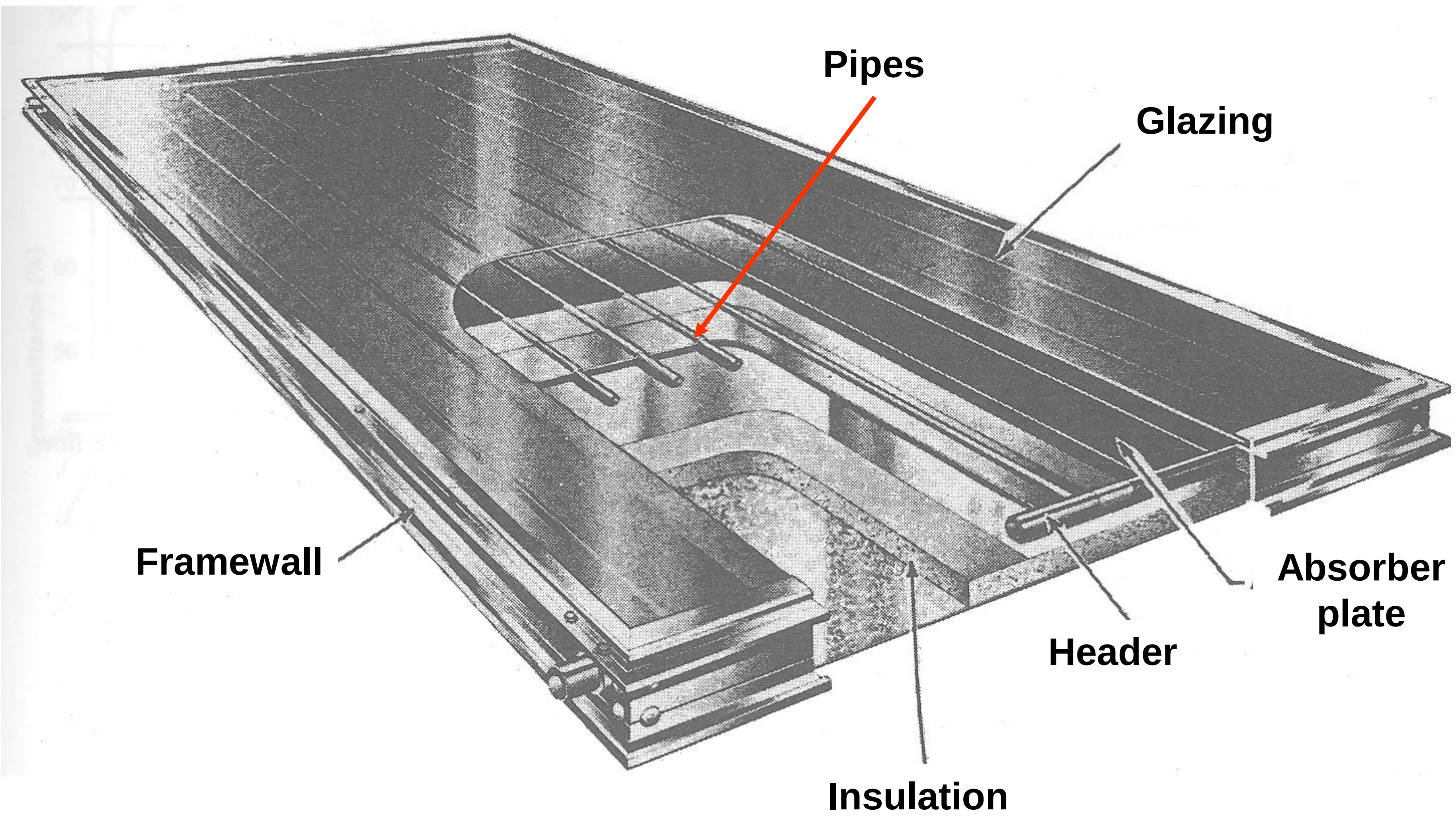


Monobloc (thermosiphon) passive system

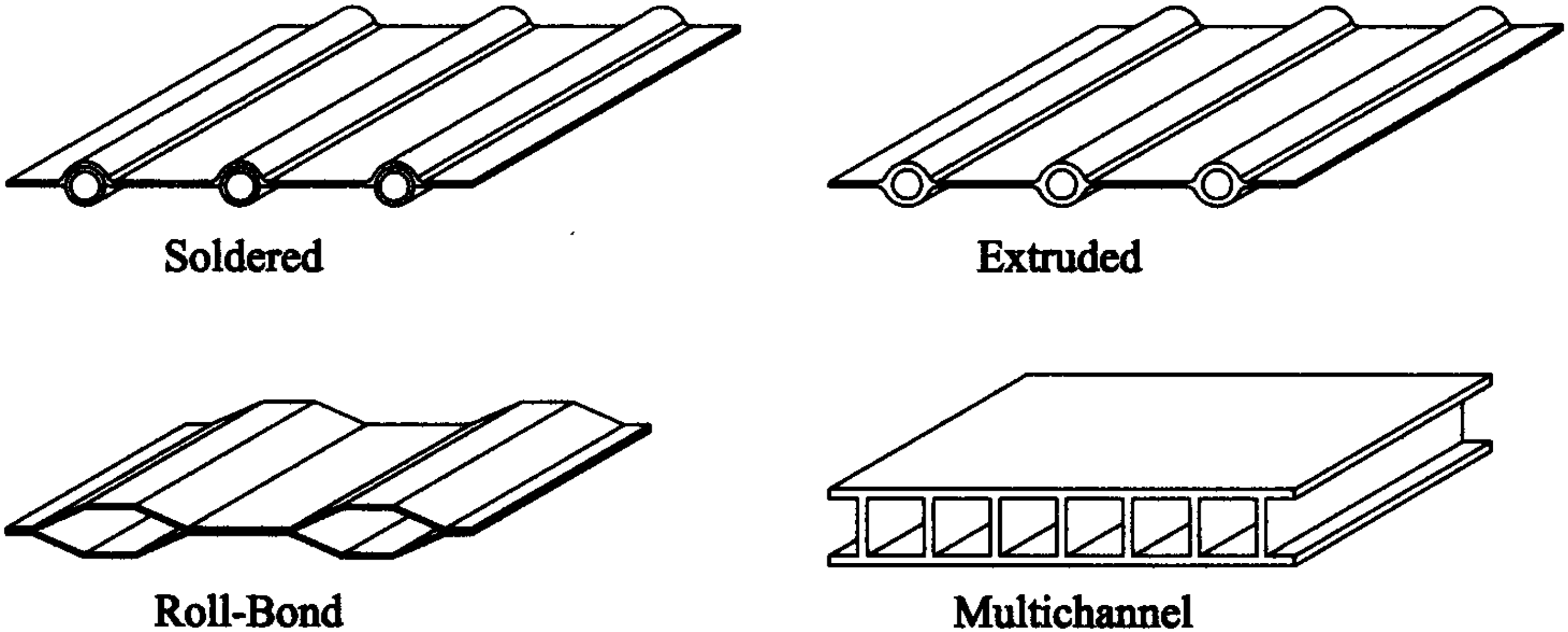


Pumped system

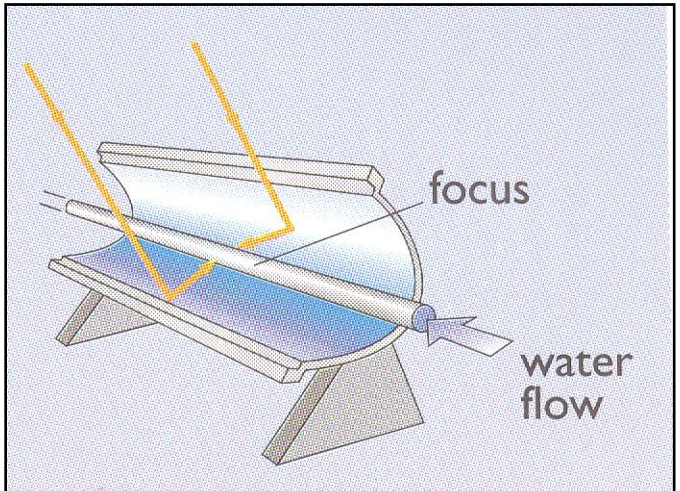
Thermal solar panel



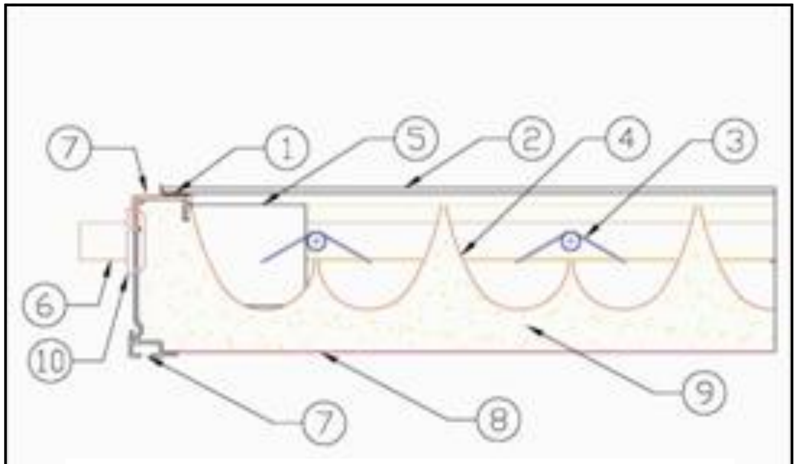
Commum types of aborber plates



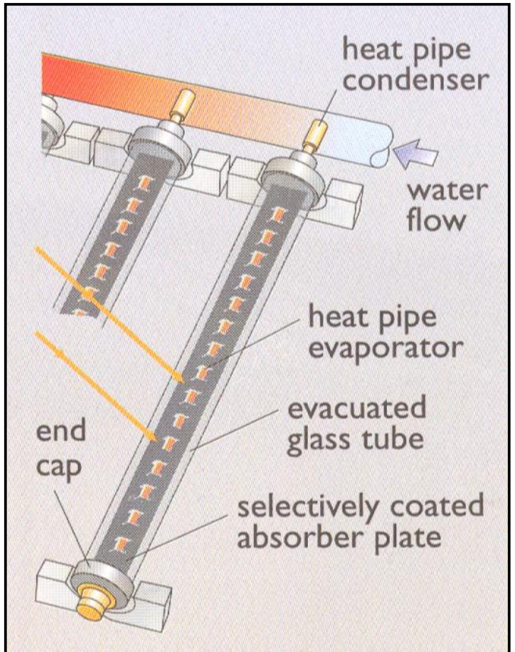
Materials: copper, aluminium, stainless steel, galvanized steel



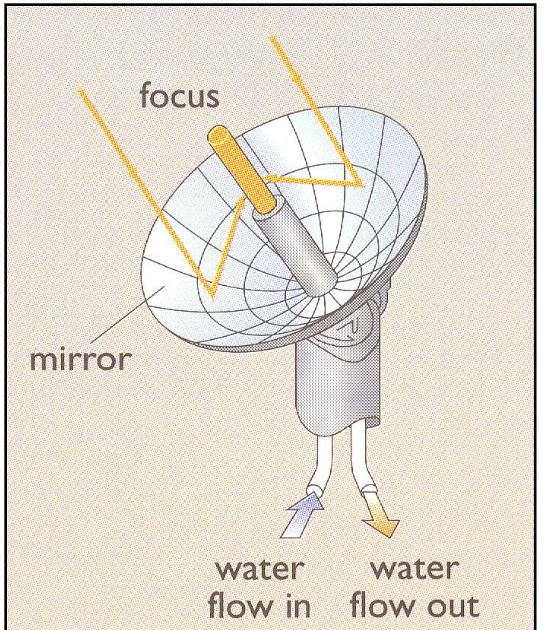
LINE FOCUS
50–150 °C RISE



CPC (Compound Parabollic Concentrator) panel

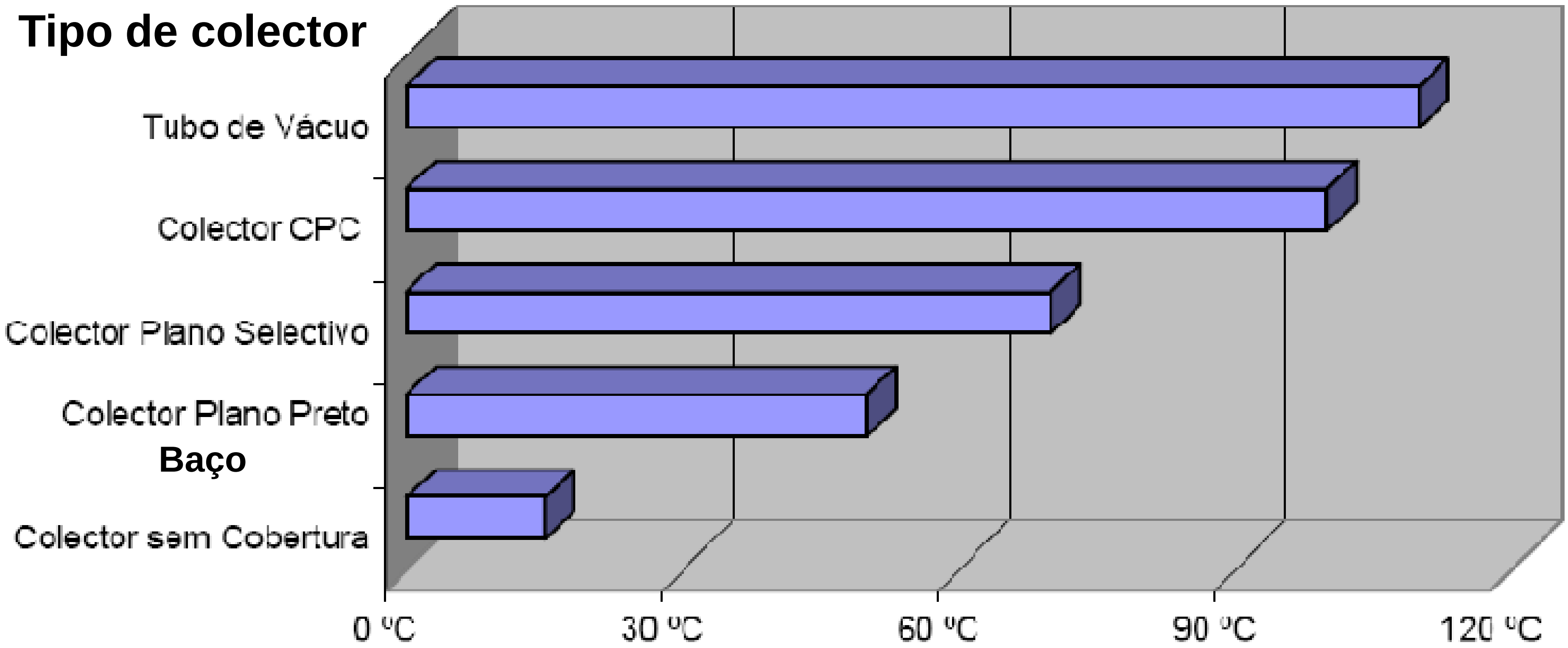


EVACUATED TUBE
10–150 °C RISE



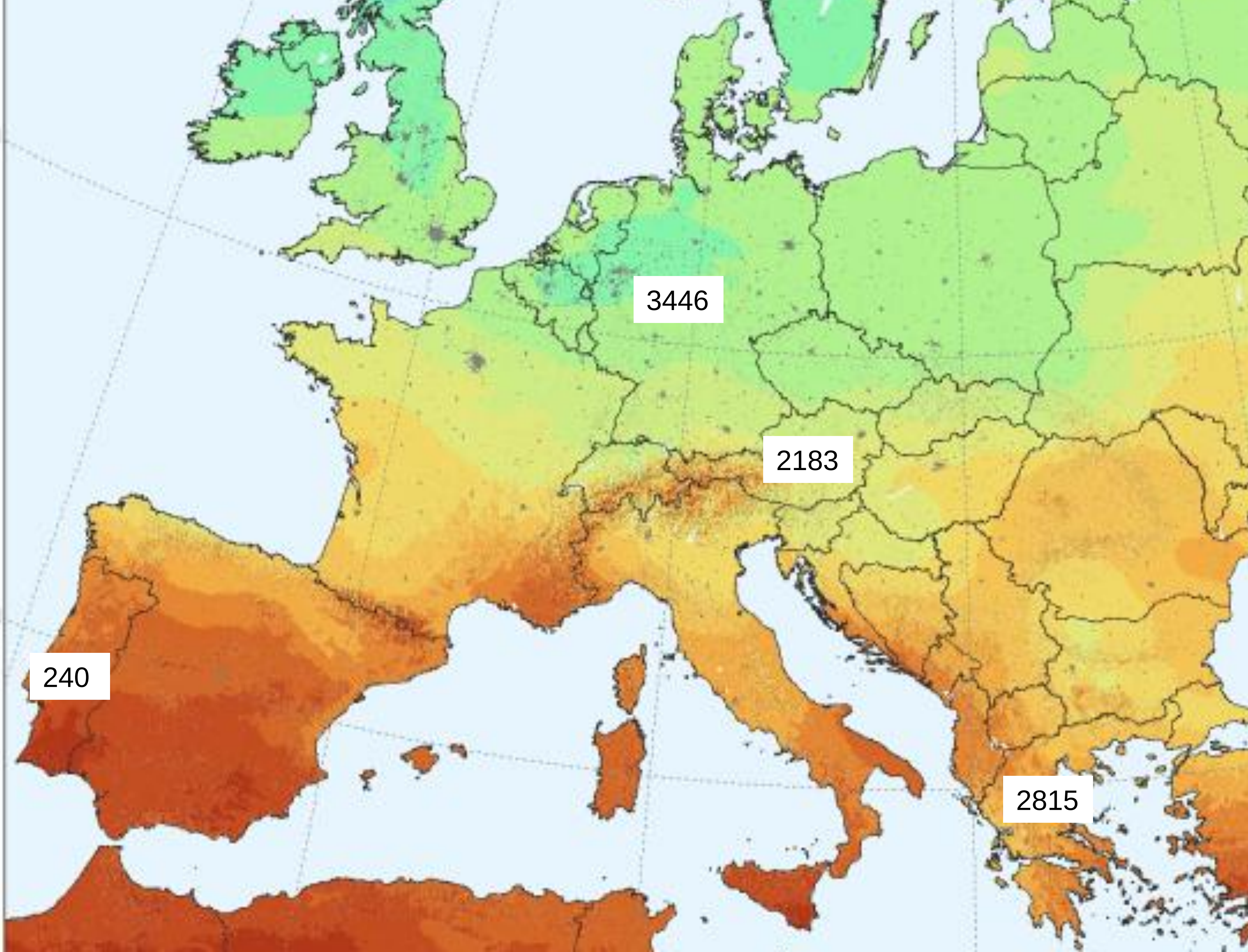
POINT FOCUS
>100 °C RISE

Increase in water temperature



Total thermal collector area in operation in the year 2000 in IEA member countries

Country	Water collectors			AIR COLLECTOR		TOTAL
	unglazed	glazed	evacuated tube	unglazed	glazed	
Australia						
Austria	571,806	1,581,185	26,219		3,500	2,182,710
Belgium	21,875	19,400	1,700			42,975
Canada	493,000	72,000	509	41,000	0	606,509
Denmark	15,563	243,169				258,732
Finland		10,200	100			10,300
France	84,500	470,000				554,500
Germany	615,000	2,399,000	392,000		40,000	3,446,000
Greece		2,815,000				2,815,000
Italy	20,000	300,000	20,000	2,000	2,000	344,000
Japan		11,445,008	307,481			11,752,489
Mexico	283,800	94,600				378,400
The Netherlands	100,305	176,580		5,341		282,226
New Zealand		64,000				64,000
Norway	500	7,000	100		1,000	8,600
Portugal	1,000	238,000	500			239,500
Spain		399,922				399,922
Sweden	30,000	175,045	3,000			208,045
Switzerland	221,200	250,800	15,000	816,000		1,303,000
Turkey	0	7,500,000	0	0	0	7,500,000
United Kingdom	0	149,000	2,000			151,000
United States	14,513,000	8,277,000	2,390,000		439,000	25,619,000
TOTAL	**16,971,549**	**36,686,909**	**3,158,609**	**864,341**	**485,500**	**58,166,908**


3446
2183
240
2815

Decreto-Lei nº 80/206 de 4 de Abril

Aprova o **Regulamento das Características de Comportamento Térmico dos Edifícios (RCCTE).**

Duplica os requisitos nos edifícios novos e objecto de reabilitação e impõe a utilização de colectores solares para aquecimento de água.

Capítulo III, Artigo 7º

2 – O recurso a sistemas de colectores solares térmicos para aquecimento de água sanitária nos edifícios abrangidos pelo RCCTE **é obrigatório** sempre que haja uma exposição solar adequada, na base de $1m^2$ de colector por ocupante convencional previsto., …, podendo este valor ser reduzido por forma a não ultrapassar 50% da área de cobertura total disponível, em terraço ou nas vertentes orientadas no quadrante sul, entre sudeste e sudoeste.

Solar water heating

The situation in Greece: how different is the situation in Portugal?

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Investigating the real situation of Greek solar water heating market

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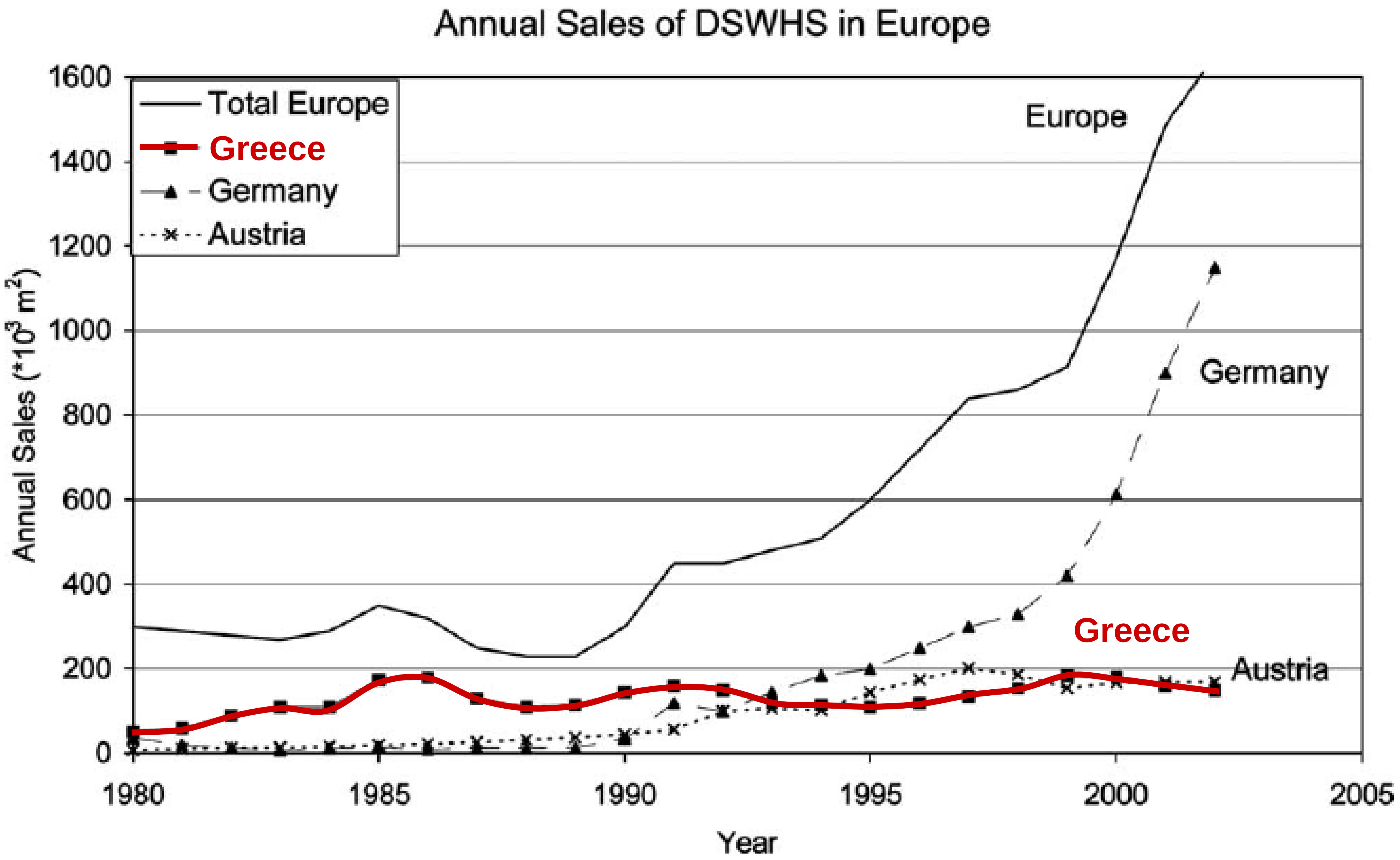
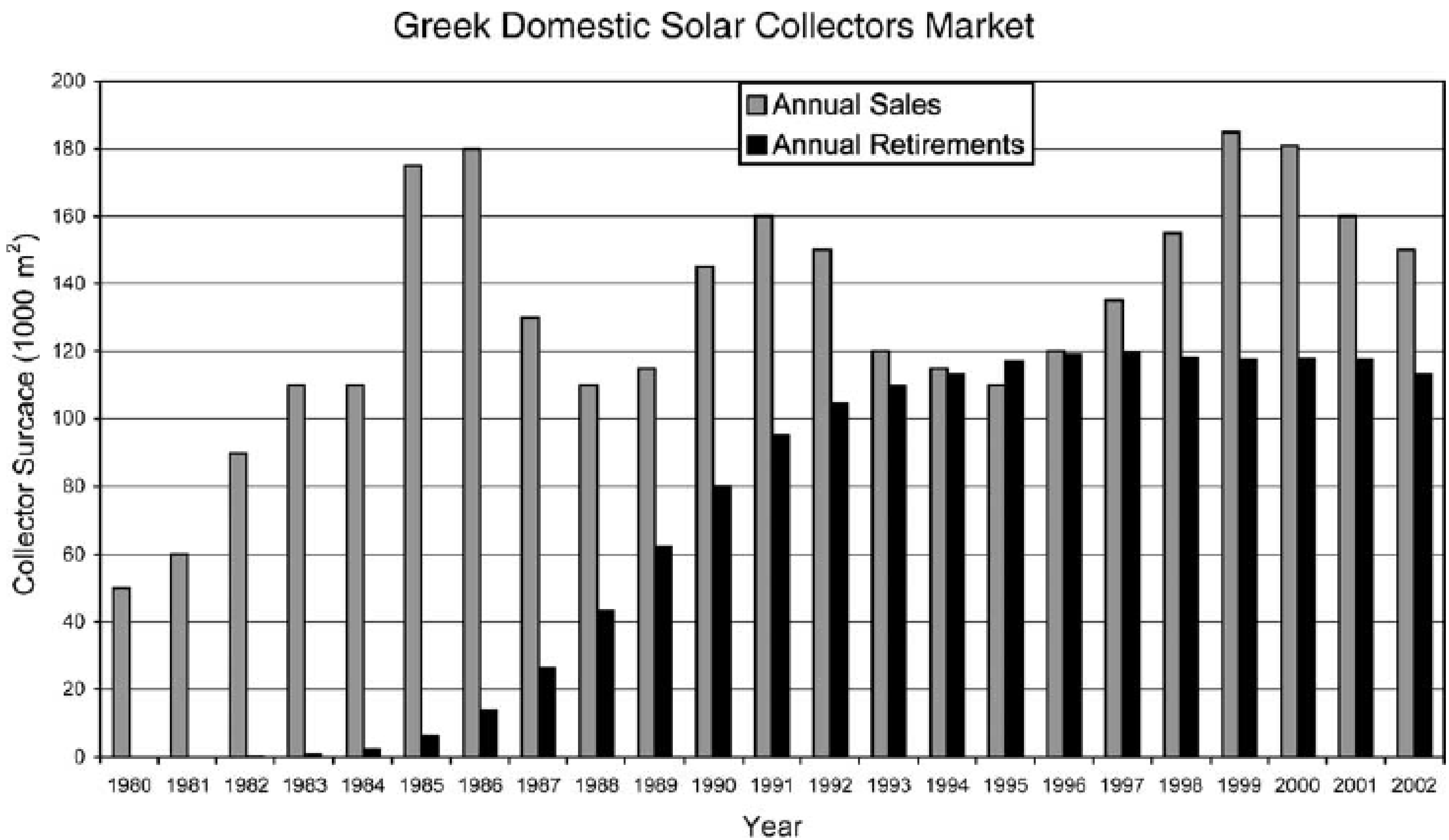
Domestic Solar Water Heating System (DSWHS)

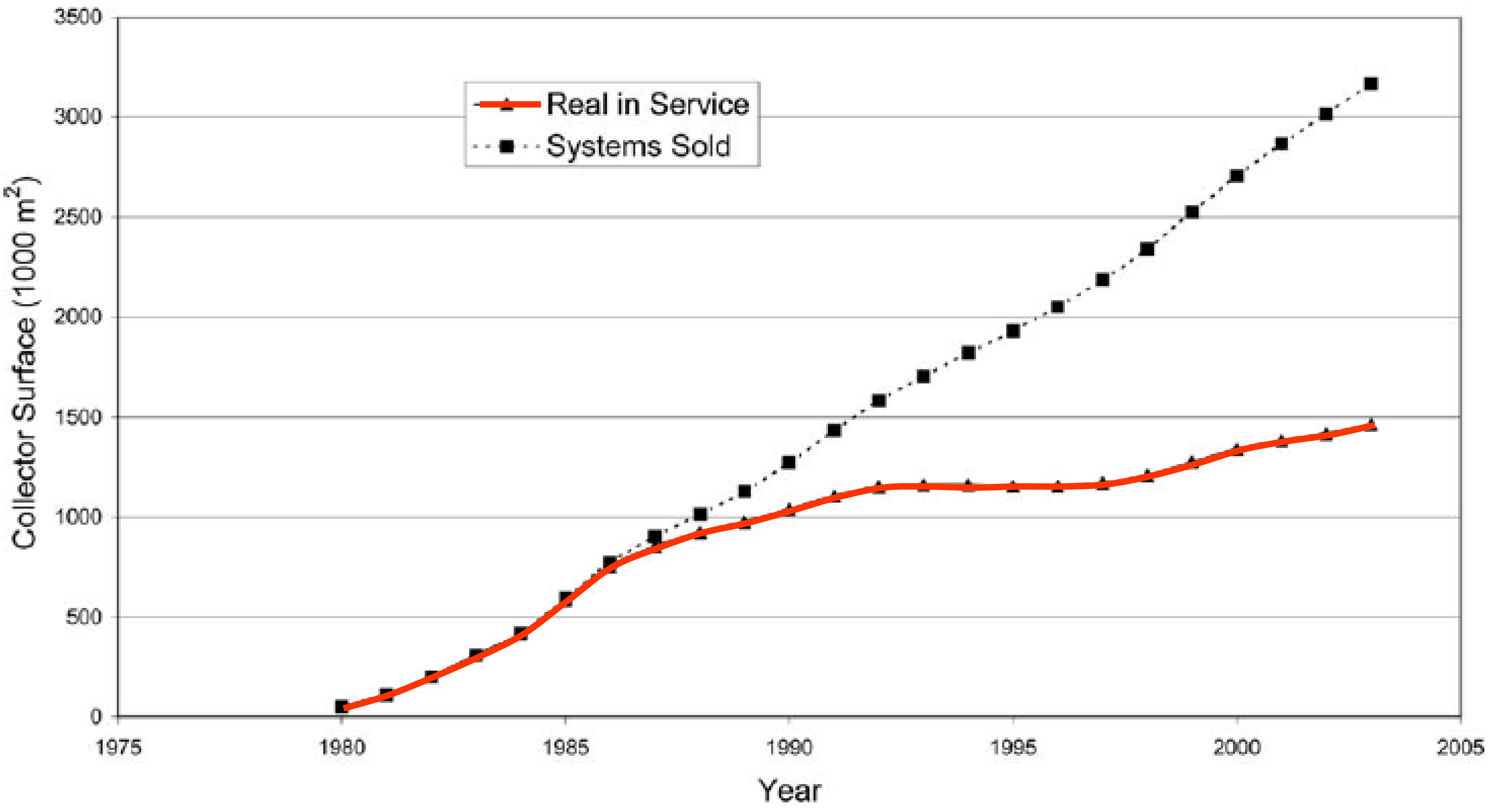


Note the increase in sales in Germany and Austria since 1990, and the stagnation in Greece after a fast start in the late 1970s and early 1980s.

Comparison between new installed and retired DSWHSs is Greece

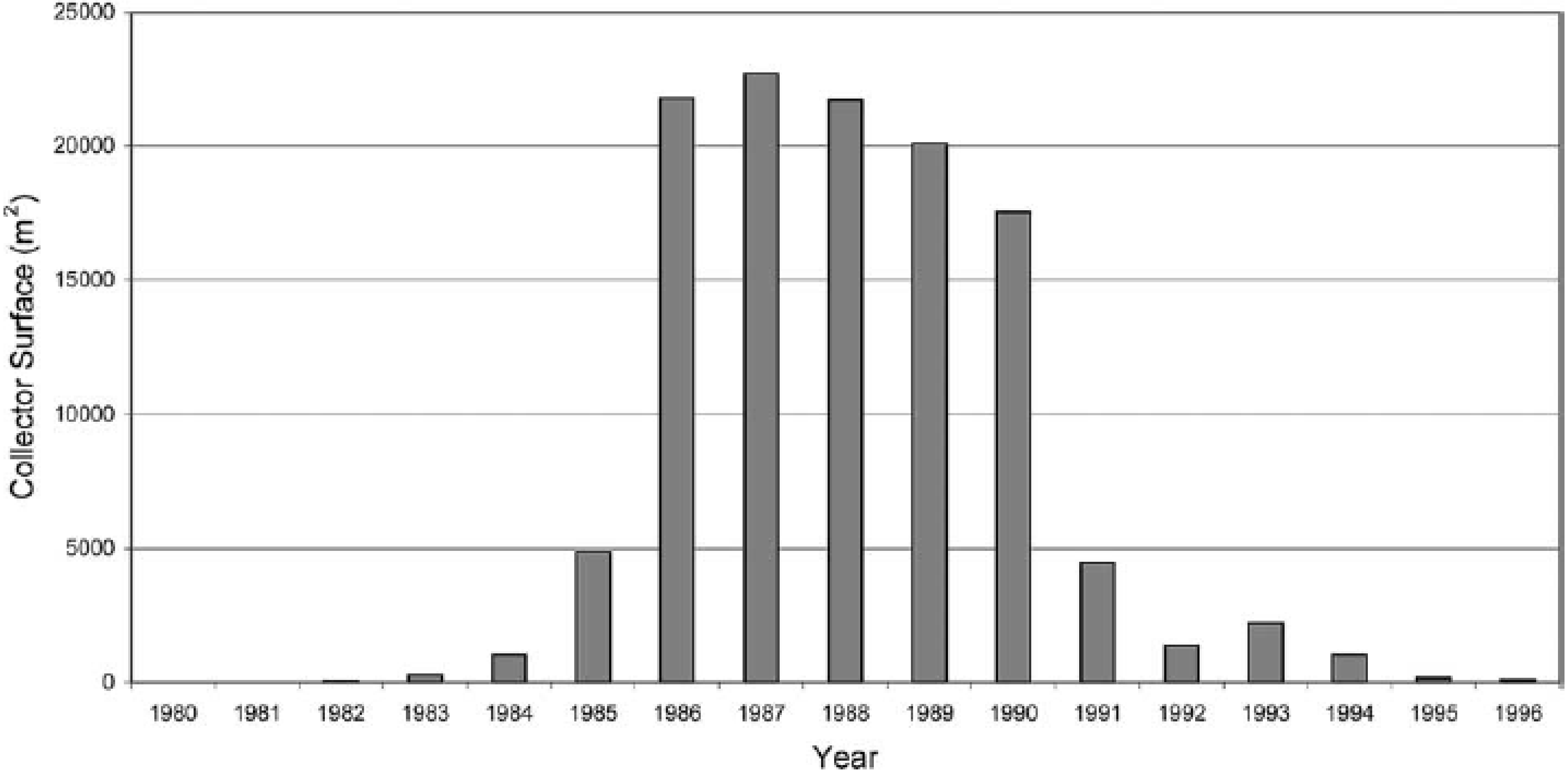


Time-evolution of cumulative DSWHS in operation (Greece)



Note that it is important to subtract the number of systems retired from service, otherwise the number for cumulative sales may be misleading.

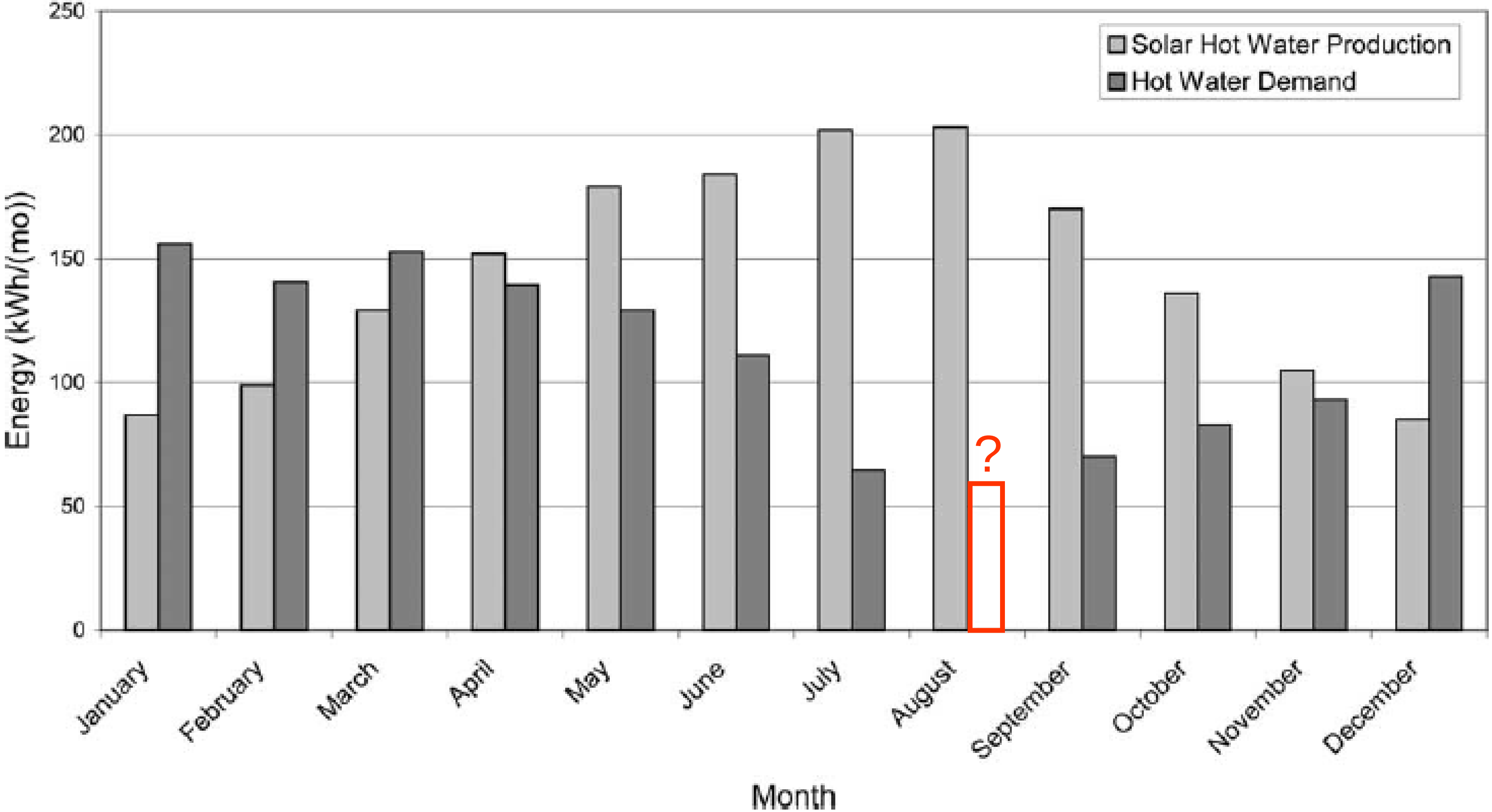
Analysis of DSWHSs retired in 1997 according to their installation year



Lifespan of DSWHSs installed in 1986-90: 7-11 years.

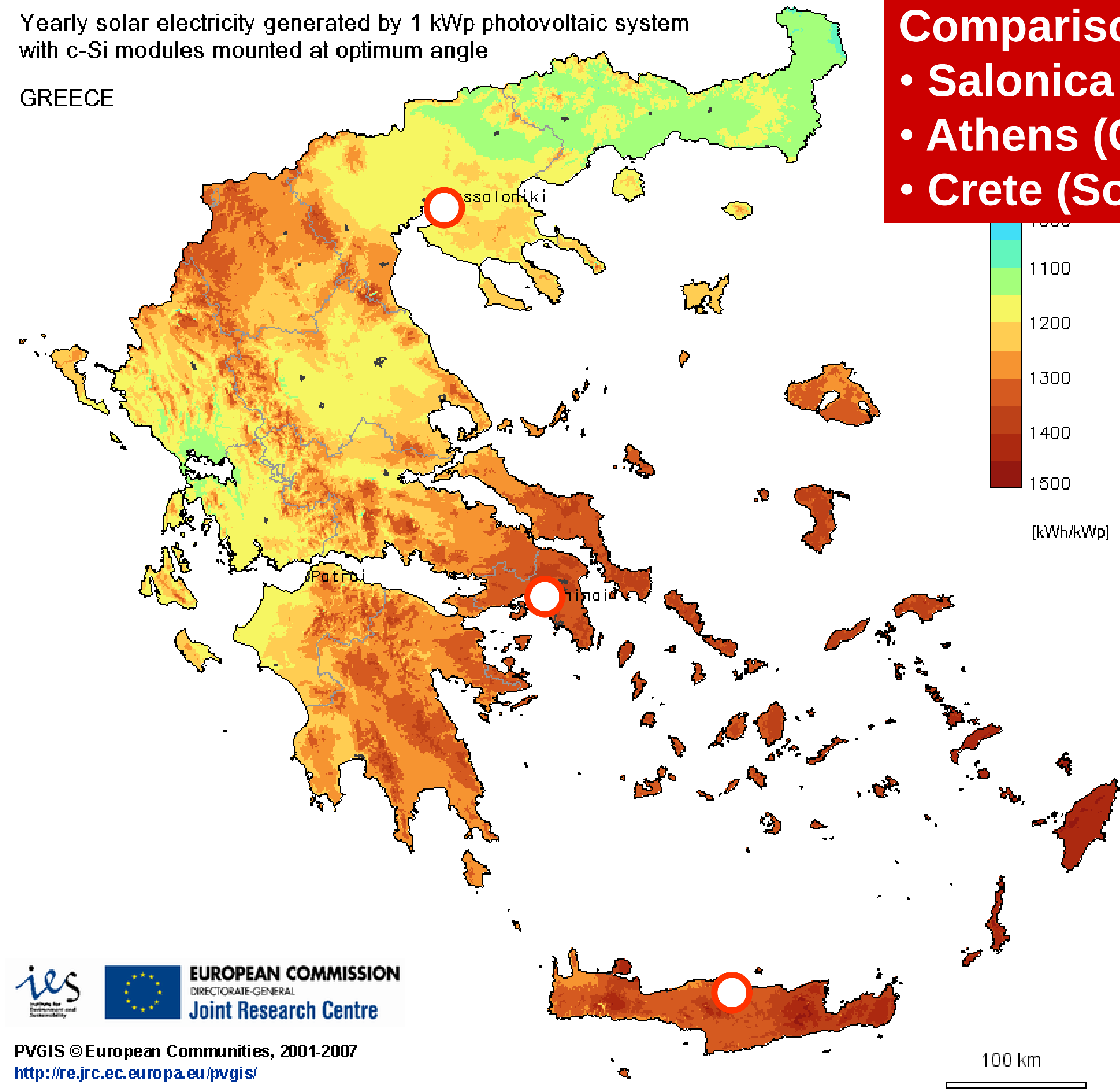
Very few systems sold and installed in the late 1970s and early 1980s were still in operation in 1997.

Comparison between hot water demand and solar production (Four persons per family, collector area A_c = 2.5 m^2)

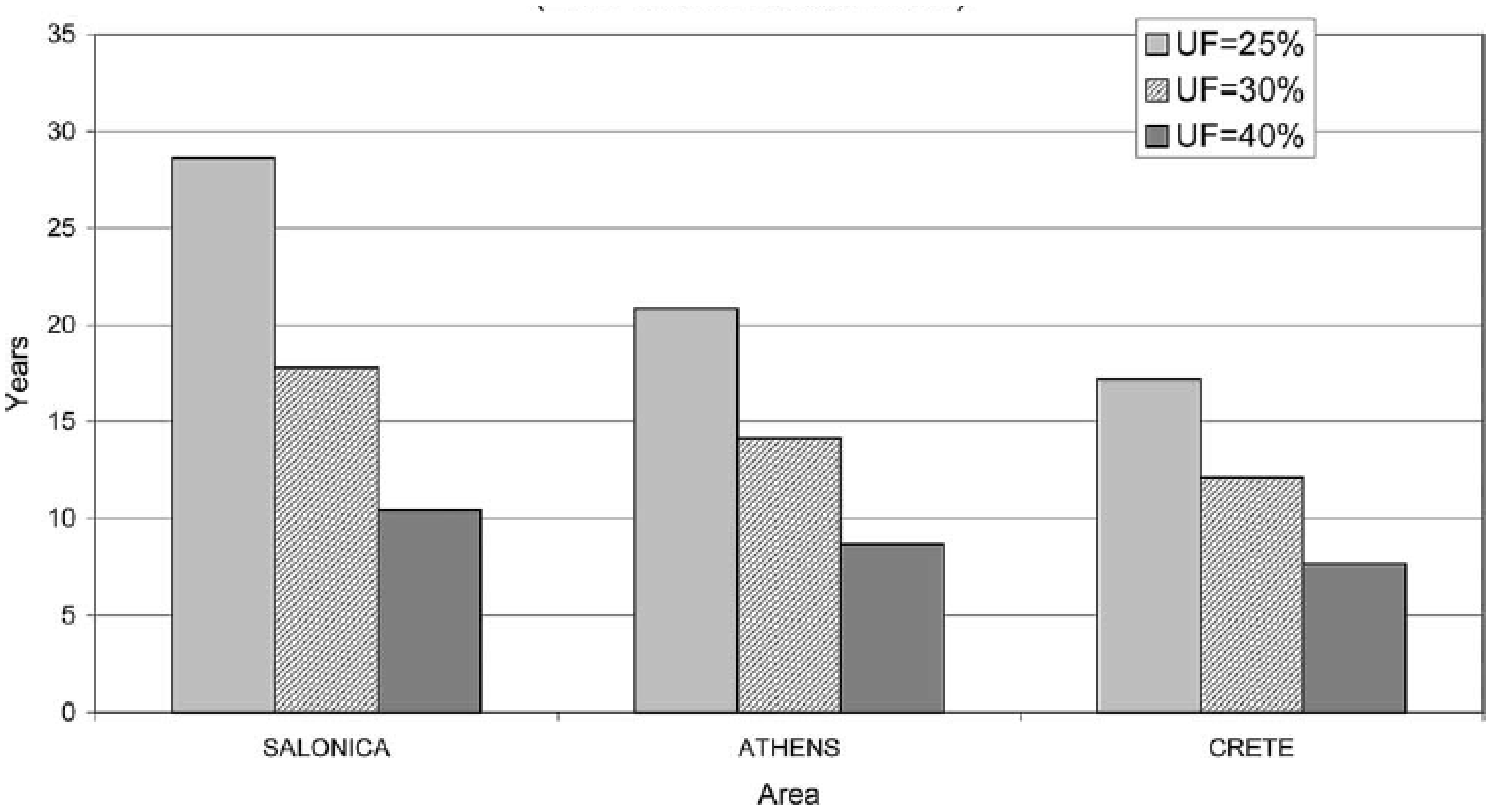


Note that the solar hot water exceeds the demand in the warmer and sunnier months, and is insufficient in the other months.

Comparison of 3 areas:
- Salonica (North)
- Athens (Centre)
- Crete (South)

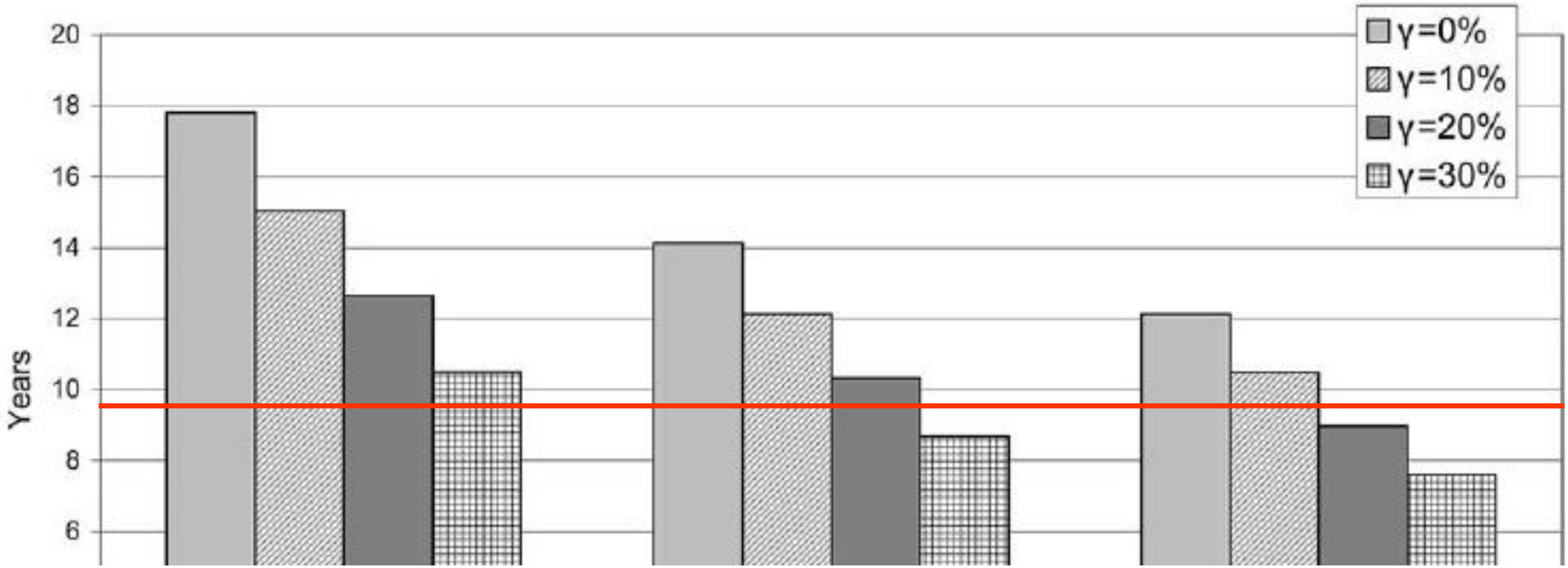


Payback period of DSWHS in Greece (zero State subsidization) depending on location and utilization factor (UF).



Note that the payback period decreses with greater utilization and with the increasing solar energy available (north to south).

Payback period of DSWHS in Greece (medium utilization factor UF = 30%) depending on area and on subsidization percentage γ.



Setting acceptable payback period = 9.5 years (75% of systems should operate over > 9.5 years) and UF = 30%, the necessary subsidization percentage should be:

- 35% in Northern Greece (Salonica)
- 25% in Central Greece (Athens)
- 17% in South Greece (Crete)

Photovoltaic solar conversion

PHOTOVOLTAICS

Direct conversion of sunlight into electricity

Wide range of applications:

- Micro: calculators, watches,…
- Small and medium: remote houses, water pumping, telecommunications, parkmeters, …
- Space: satellites, space vehicles.
- Large: power plants, up to several hundred MW.

History:

- Becquerel (1839): photovoltaic effect in electrolyte liquids.
- Adams & Day (1877): PV effect in solids (selenium).
- 1954 (USA): modern technologies with semiconductors (6% efficiency).
- Space race USA-URSS resulted in dramatic progress in PV.

PHOTOVOLTAICS

In early days (1960s and 1970s): more energy produced in cell fabrication than produced by cell during lifetime.

Presently: pay-back energy in 2.5 to 5 years.

Little maintenance requirements (no moving parts).

Panel lifetime > 25 years.

Cost per unit energy: **high, but decreasing**.

Competitive (or only solution) in special applications (space, …).

(Not yet) competitive with conventional plants (including wind), except if special feed-in tariffs are applied (as in Portugal).

How to convert sunlight directly into electricity?

Modern physics (Einstein, Planck, …) explains that **light** may be regarded as having **wave** properties and **particle** properties (**wave**-**particle** duality).

The energy of the particle (**photon**) is proportional to wave frequency.

Electrical current is a flow of **electrons**.

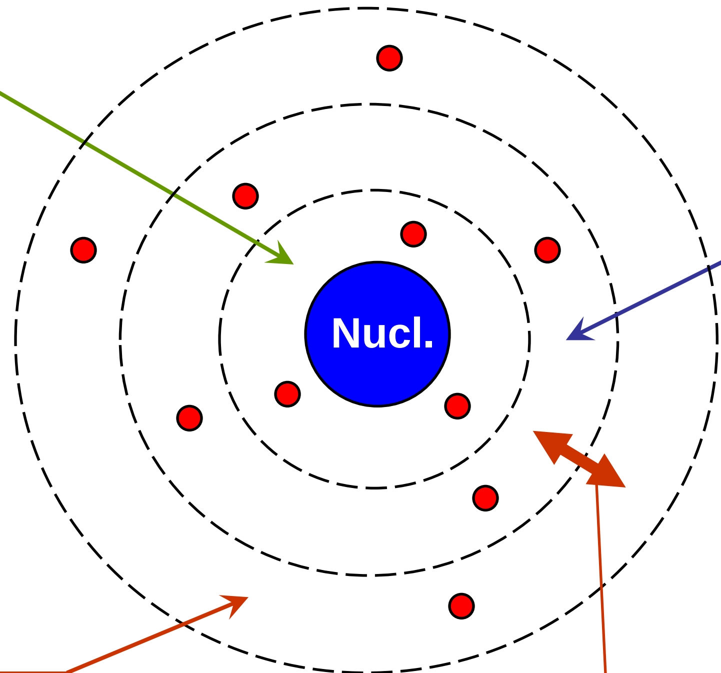
The conversion of sunlight into electricity involves a transfer of energy from **photons** to **electrons**.

This is done in special **cells** made of **semiconductors**.

Electrons in the atom

Inner band(s);
little energy;
strongly bound
to nucleous

Valence band;
intermediate energy;
provide bonds with
other atoms



Conduction band;
high energy;
free to circulate;
conduction of heat
and electricity

Band gap = B.G. = energy difference between electrons in conduction and valence bands

MATERIALS

Insulators

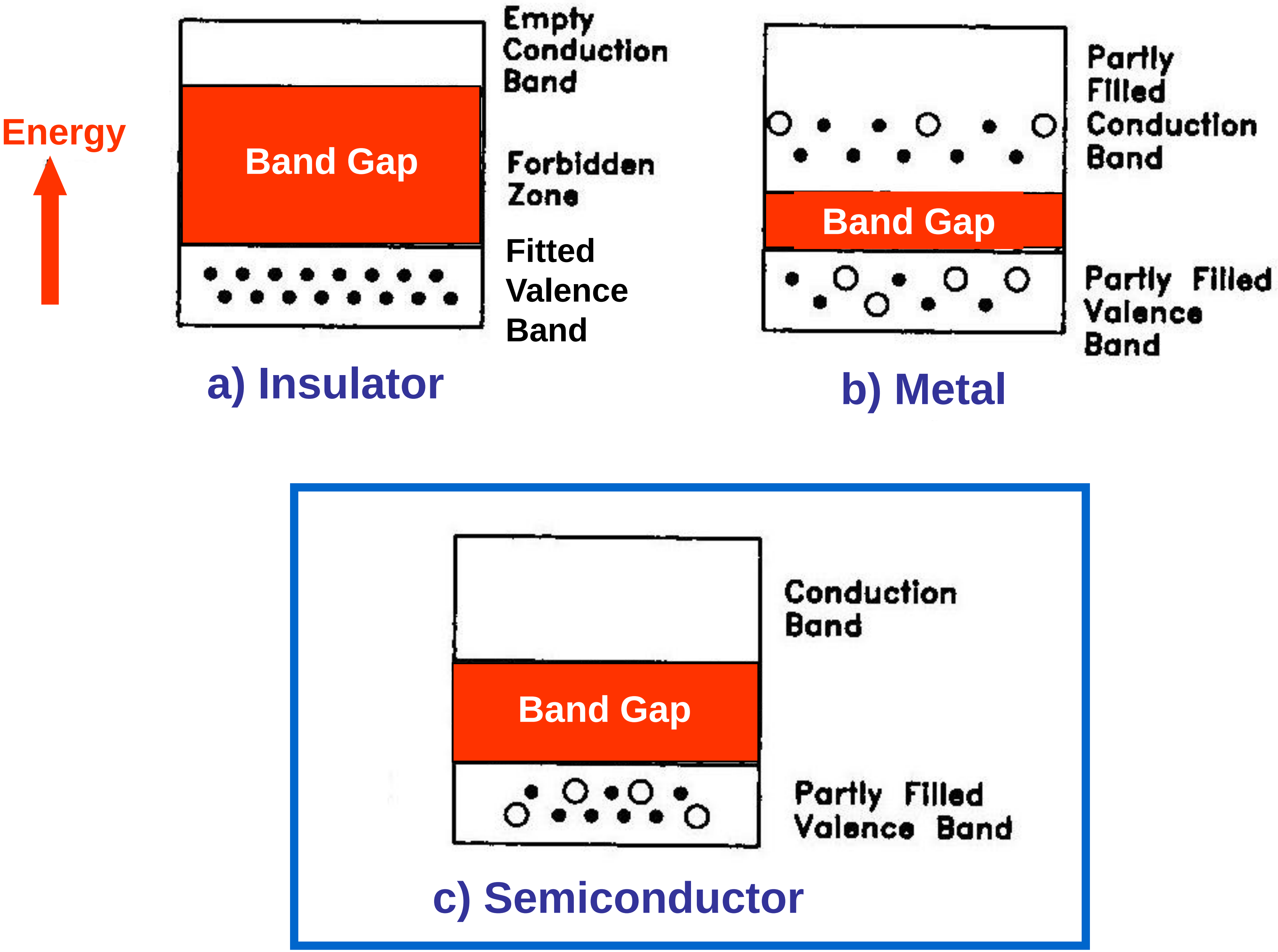
- valence bands are full
- large band gap BG > 3 eV

Conductors (e.g. metals)

- valence bands are relatively empty
- small band gap BG << 3 eV

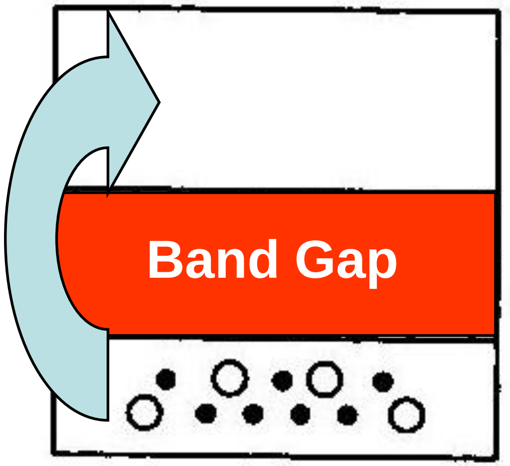
Semiconductors

- valence bands are partly filled
- intermediate band gap BG < 3 eV


Energy
Band Gap
Empty Conduction Band
Forbidden Zone
Fitted Valence Band
a) Insulator
Band Gap
Partly Filled Conduction Band
Partly Filled Valence Band
b) Metal
Band Gap
Conduction Band
Partly Filled Valence Band
c) Semiconductor

The basic mechanism of PV

An **electron** in the valence band may jump to the conduction band (and contribute to electrical current) if it receives the required energy for the jump (= **Band Gap**).



This energy may be provided by a **photon**.

The process takes place in a **cell** made up of **semiconductors.**

Photovoltaic effect

- For electrons in the valence band to jump to conduction band, they need external energy.
- This may be provided by solar radiation, or **photons**.
- Energy of a photon = E_p .

- When an electron in the valence band absorbs a photon, its energy is increased by E_p .
- If $\boxed{E_p \geq \text{B.G.}}$, the electron jumps from valence to conduction band, and contributes to the photovoltaic effect.

- The **Band Gap B.G.** depends on the material (**semiconductor**) (see table in next slide).
- The energy of the photon E_p depends on frequency (or wavelength).

Band Gap for some candidate materials for photovoltaic cells

Material	Band Gap (eV)	Material	Band Gap (eV)
Si	1.11	$CuInTe_2$	0.90
SiC	2.60	InP	1.27
$CdAs_2$	1.00	In_2Te_3	1.20
CdTe	1.44	In_2O_3	2.80
CdSe	1.74	Zn_3P_2	1.60
CdS	2.42	ZnTe	2.20
$CdSnO_4$	2.90	ZnSe	2.60
GaAs	1.40	AlP	2.43
GaP	2.24	AlSb	1.63
Cu_2S	1.80	As_2Se_3	1.60
CuO	2.00	Sb_2Se_3	1.20
Cu_2Se	1.40	Ge	0.67
$CuInS_2$	1.50	Se	1.60
$CuInSe_2$	1.01		

Energy of the photon E_p : depends on frequency of solar radiation

$$\boxed{E_p = hf = \frac{hc}{\lambda}}$$

$h = 6.625 \times 10^{-34}$ J·s = constant of Planck

$f = \dfrac{c}{\lambda}$ = frequency of radiation $\qquad \lambda$ = wavelength

$c = 3.0 \times 10^{8}$ m/s = velocity of light (in vacuum)

Units : 1 eV = 1.602×10^{-19} J

Do not forget that (unlike a laser beam) sun light is polychromatic, i.e. has a range of wavelegths (or frequencies) over a spectral distribution.

Band Gap (G.P.): depends on the material (semiconductor) (see Table in previous slide).

For the most commonly used material (silicon) B.G. = 1.1 eV .

What happens when a photon meets an electron of the valence band ?

a) If $E_p < B.G.$ The energy of the photon is not enough for the electron to jump from the valence band to the conduction band. The photon may go through the semiconductor layer or its energy may be wasted as increase in temperature.

b) If $E_p = B.G.$ The energy of the photon is exactly what is needed for the electron to jump from the valence band to the conduction band. The photon is absorbed and the PV conversion is achieved with 100% efficiency.

c) If $E_p > B.G.$ The energy of the photon exceeds what is needed for the electron to jump from the valence band to the conduction band. The difference $E_p - B.G.$ is wasted as increase in temperature. The photovoltaic conversion is achieved with less than 100% efficiency.

Which fraction of solar radiation energy can be used by photovoltaic effect ?

$$E_p(\lambda,T)=\frac{hc}{\lambda}=\mathrm{B.G.}\quad\Rightarrow\quad\lambda=\lambda_0=\frac{hc}{\mathrm{B.G.}}$$

$$E_{b\lambda}(\lambda,T)\,d\lambda=\text{radiated energy flux in wavelength interval }(\lambda,\lambda+d\lambda)$$

In the range $\lambda>\lambda_0$, in which $E_p(\lambda,T)<\mathrm{B.G.}$, all the radiation energy is wasted.

In the range $\lambda<\lambda_0$, in which $E_p(\lambda,T)>\mathrm{B.G.}$, only part of the radiation energy can be used.

In interval $(\lambda,\lambda+d\lambda)$, (with $\lambda<\lambda_0$), the fraction of energy $E_{b\lambda}(\lambda,T)\,d\lambda$ that can be used is

$$\boxed{\eta_\lambda=\frac{\mathrm{B.G.}}{E_p(\lambda,T)}=\frac{\mathrm{B.G.}}{hc/\lambda}}$$

The overall maximum efficiency of a photovoltaic cell can obtained by integration

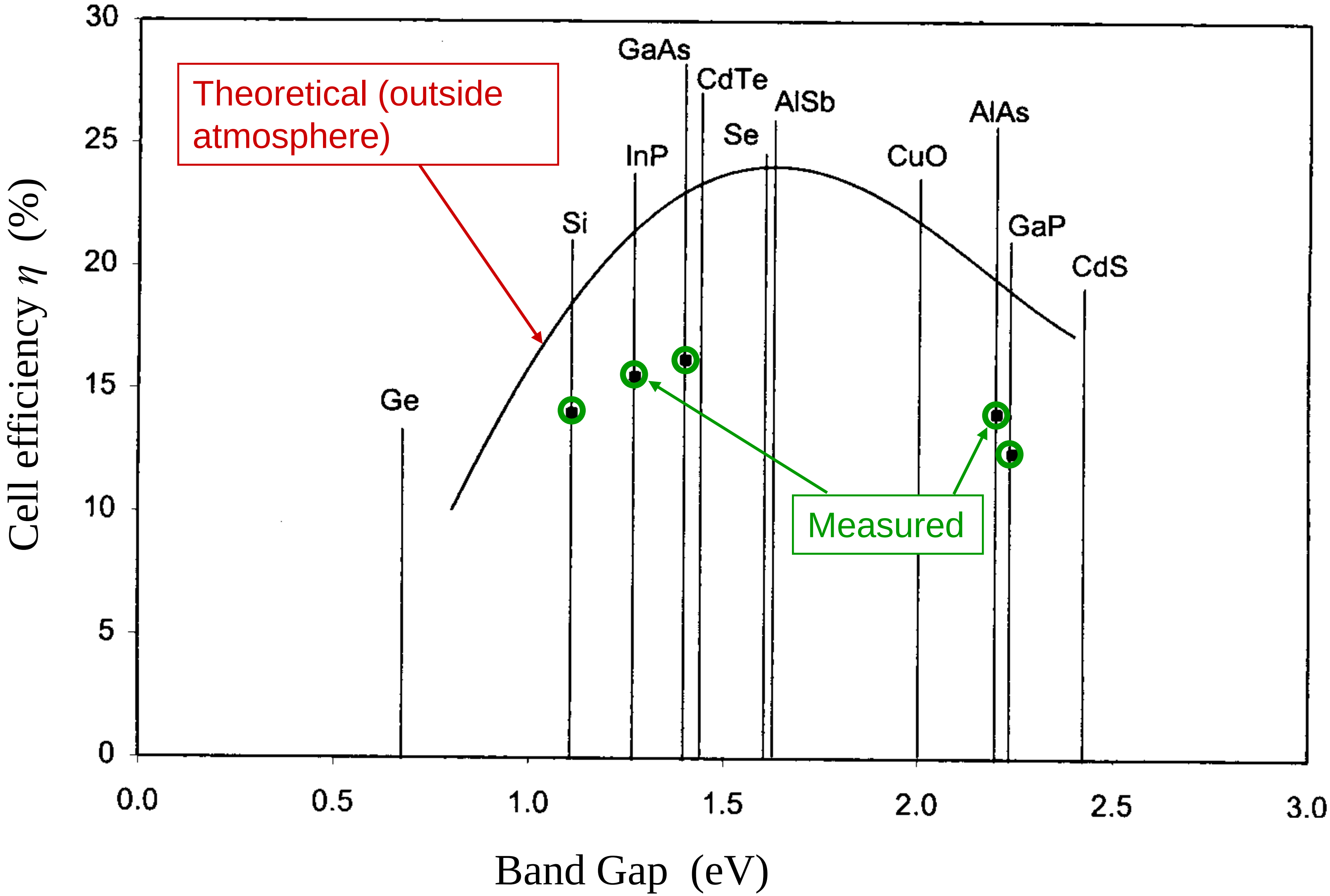
$$\boxed{\eta = \frac{\int_0^{\lambda_0} \eta_\lambda(\lambda) E_{b\lambda} d\lambda}{\int_0^{\infty} E_{b\lambda} d\lambda}}$$

This is represented by the curve in the following slide, for solar radiation outside the atmosphere.

Measured results are shown for comparison.

Note that this theoretical limit applies to **single-junction** solar cells. This can in principle be exceeded in **multi-junction** cells (made up several layers of different semiconductors).

Maximum solar energy conversion efficiency of a photovoltaic cell



Exercise

Calculate the wavelength of light capable of forming an electron-hole pair in Silicon.

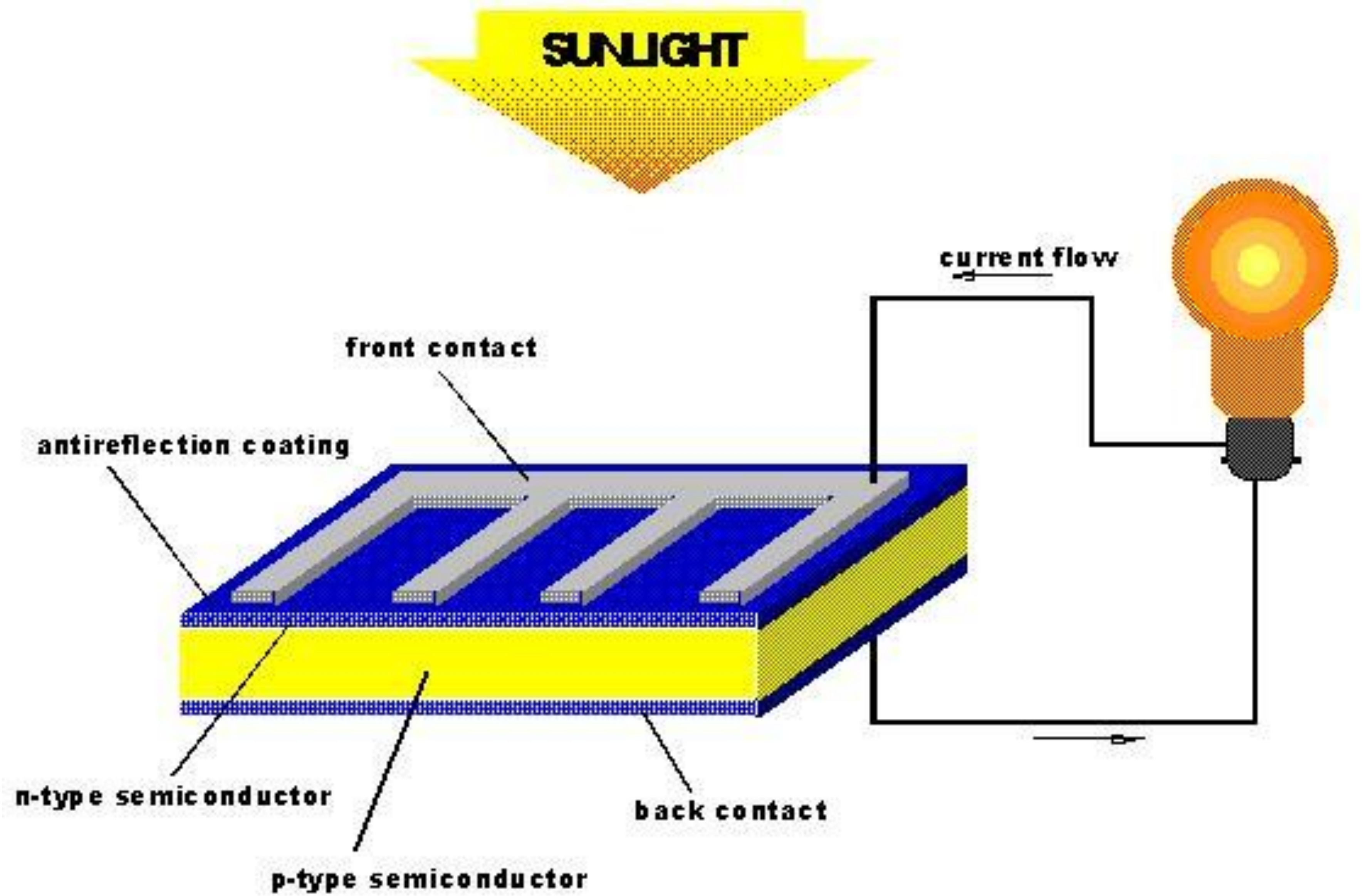
Exercise

A monochromatic **red laser beam** emitting 1 mW at a wavelength of 638 nm is incident on a Silicon solar cell.

Find:

- The number of photons per second incident on the cell.
- The maximum possible efficiency of conversion of this laser beam to electricity.

How does a photovoltaic cell work?



Semiconductors

Pure or **intrinsic semiconductors**

Doped or **extrinsic semiconductors** are doped with very small amounts of “impurities”

Silicon: the most widely used semiconductor in PV applications.

- Each atom has 4 electrons in valence band.
- Atoms form stable structures: each atom shares 2 electrons with neighbouring atoms.

Dopant materials

- If dopant material has **> 4 electrons in valence band**, the doped semiconductor is called ***n*-type** **(negative):** it has "excess" electrons (available for conduction) (but is electrically neutral).
- **Phosphorus**: has 5 electrons in valence band. Silicon doped with phosphorus is ***n*-type semiconductor**.

- If dopant material has **< 4 electrons in valence band**, the doped semiconductor is called ***p*-type** **(positive):** it has holes ("missing electrons") (but is electrically neutral).
- **Boron**: has 3 electrons in valence band. Silicon doped with boron is ***p*-type semiconductor.**

Electronic structure of atoms

Principal quantum number n				1	2		3			4	5
Azimuthal quantum number l				0	0	1	0	1	2	0	1
Letter designation of state				1s	2s	2p	3s	3p	3d	4s	4p
Z	Symbol	Element	V_i volts								
1	H	Hydrogen	13.60	1							
2	He	Helium	24.58	2							
3	Li	Lithium	5.39	Helium core	1						
4	Be	Beryllium	9.32		2						
5	B	Boron	8.30		2	1					
6	C	Carbon	11.26		2	2					
7	N	Nitrogen	14.54		2	3					
8	O	Oxygen	13.61		2	4					
9	F	Fluorine	17.42		2	5					
10	Ne	Neon	21.56		2	6					
11	Na	Sodium	5.14	Neon core			1				
12	Mg	Magnesium	7.64				2				
13	Al	Aluminum	5.98				2	1			
14	Si	Silicon	8.15				2	2			
15	P	Phosphorus	10.55				2	3			
16	S	Sulfur	10.36				2	4			
17	Cl	Chlorine	13.01				2	5			
18	A	Argon	15.76				2	6			

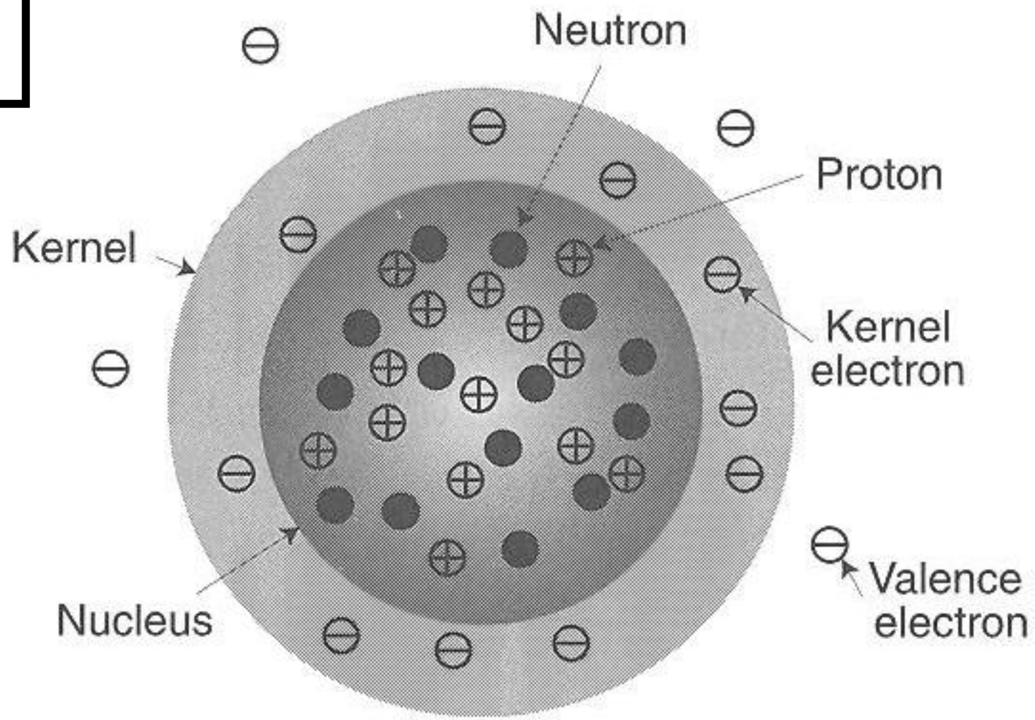
Valence band

The silicon atom

Nucleous:

14 protons (+)

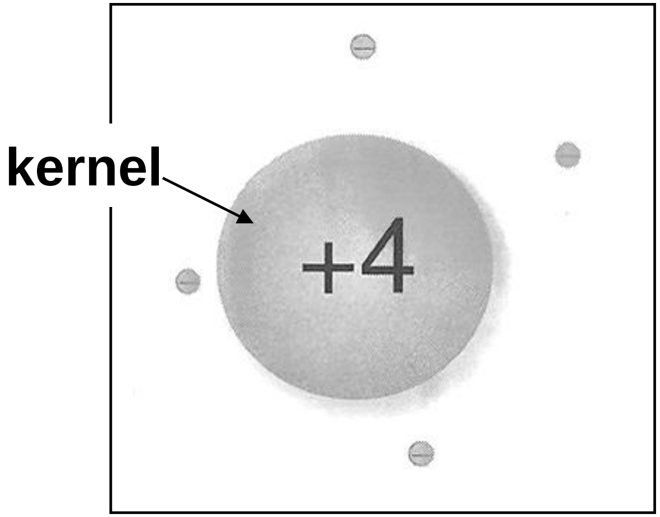
14 neutrons



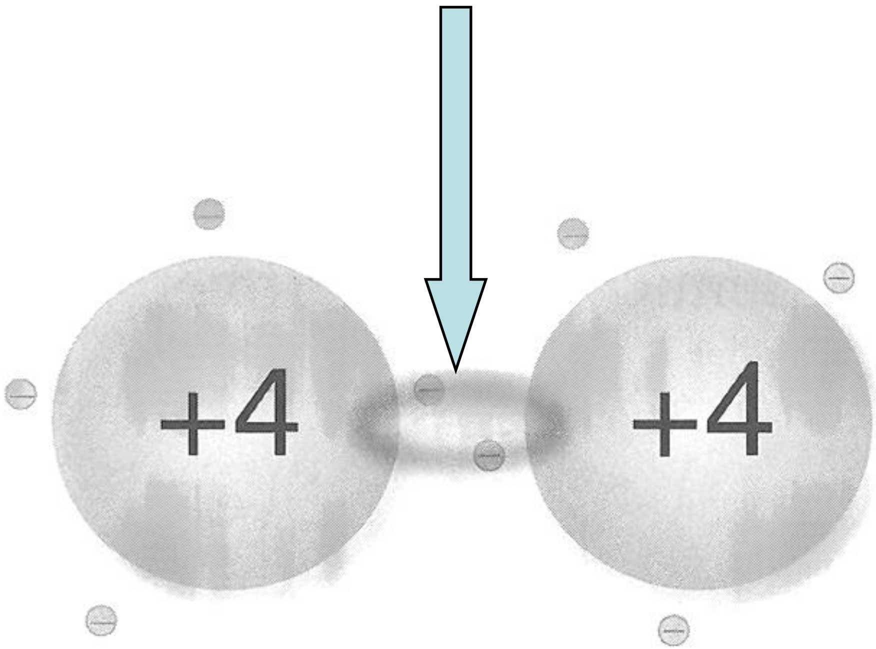
14 electrons (-):

10 in inner bands (kernel)

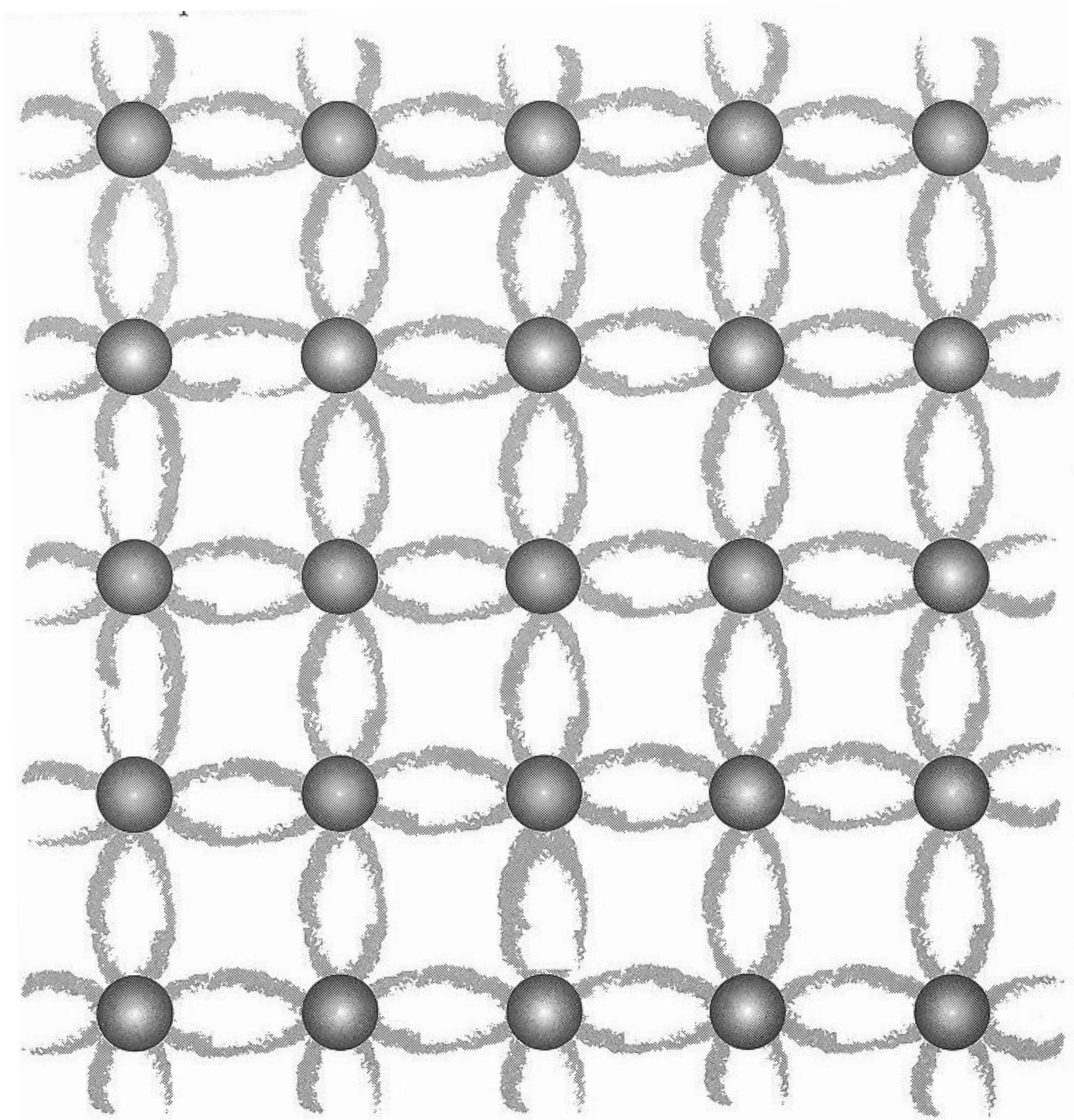
4 in valence band



Covalent bonds between
two Silicon atoms



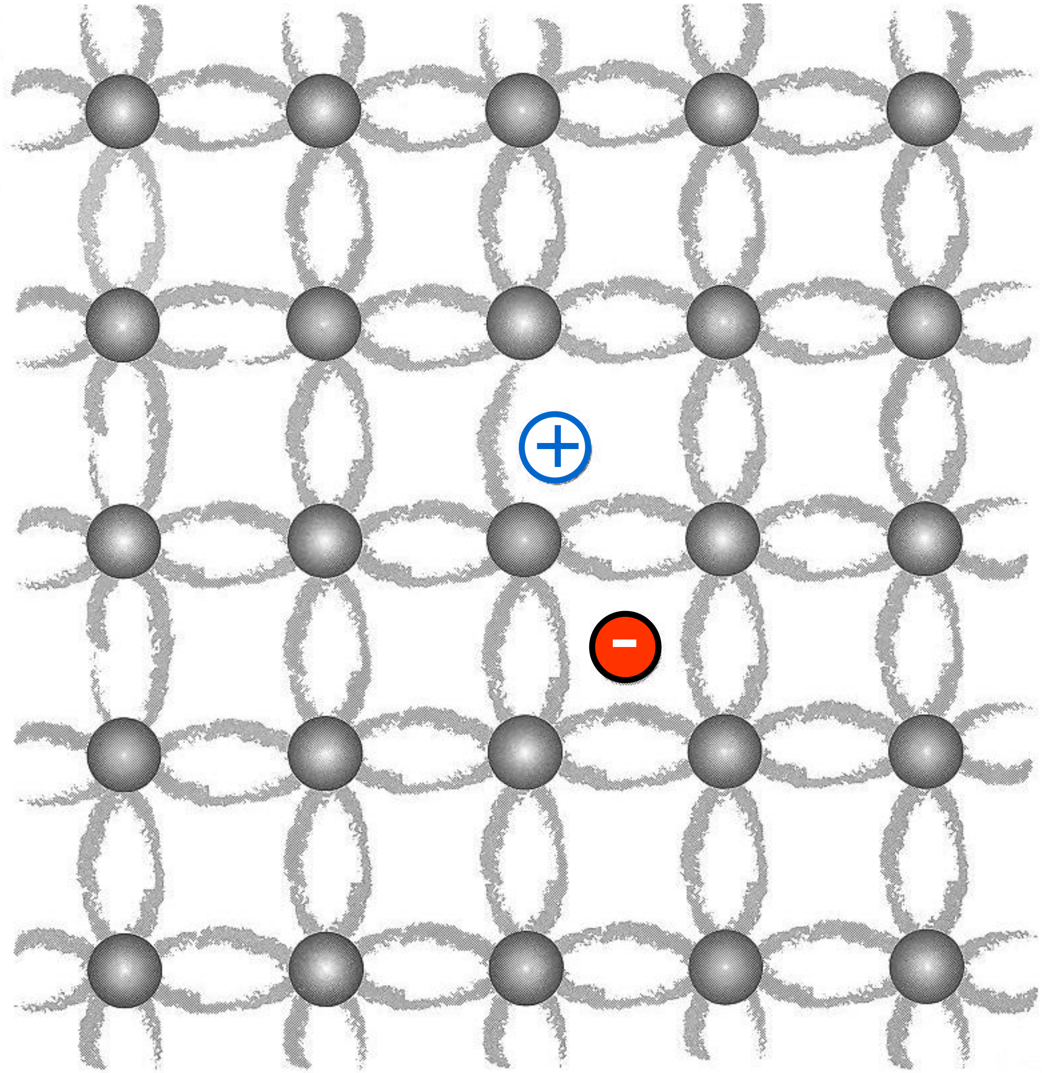
Covalent bonds between Silicon atoms (two-dimensional)



Electron from valence band that absorbed energy (from photon) and jumped to conduction band (became free)

Left a “hole”, to be filled by another electron

and can move along the lattice.



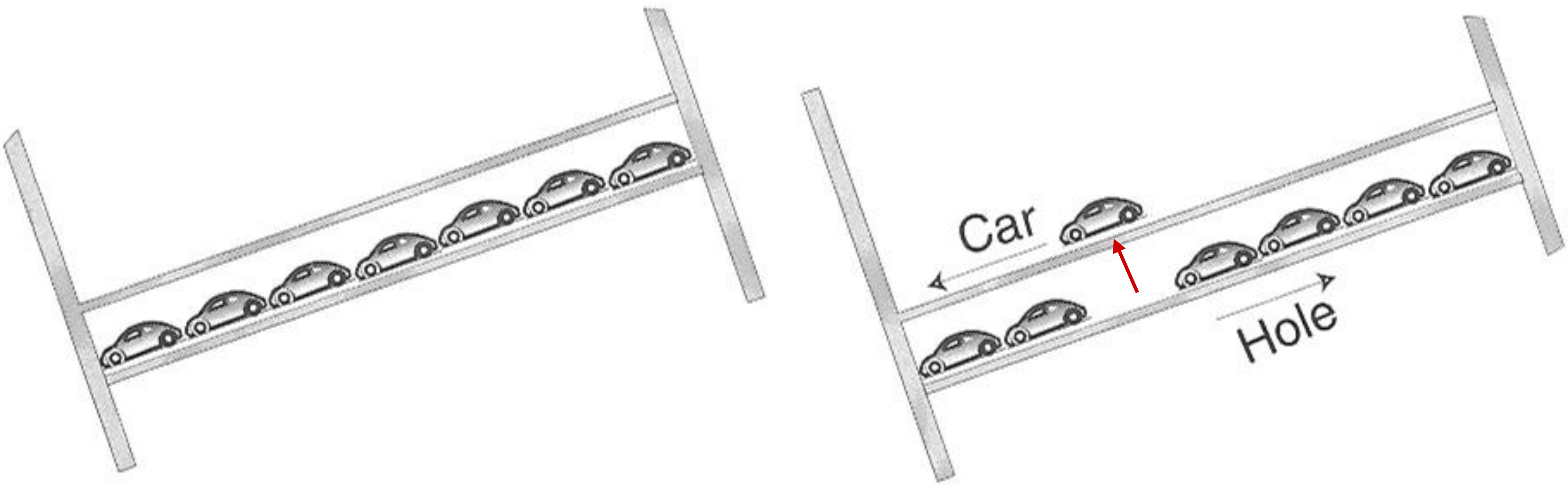
Intrinsic (pure) semiconductor: number of free electrons = number of holes

In the presence of an **electric field**, free electrons and holes move in opposite directions.

However, the resulting current is in the same direction because of the opposite charges they carry.

Analogy: cars (no brakes) in a multi-floor garage (with tilted floors).

If a **car** is hoisted to the next floor, it will roll to the left, and the **hole** will move to the right



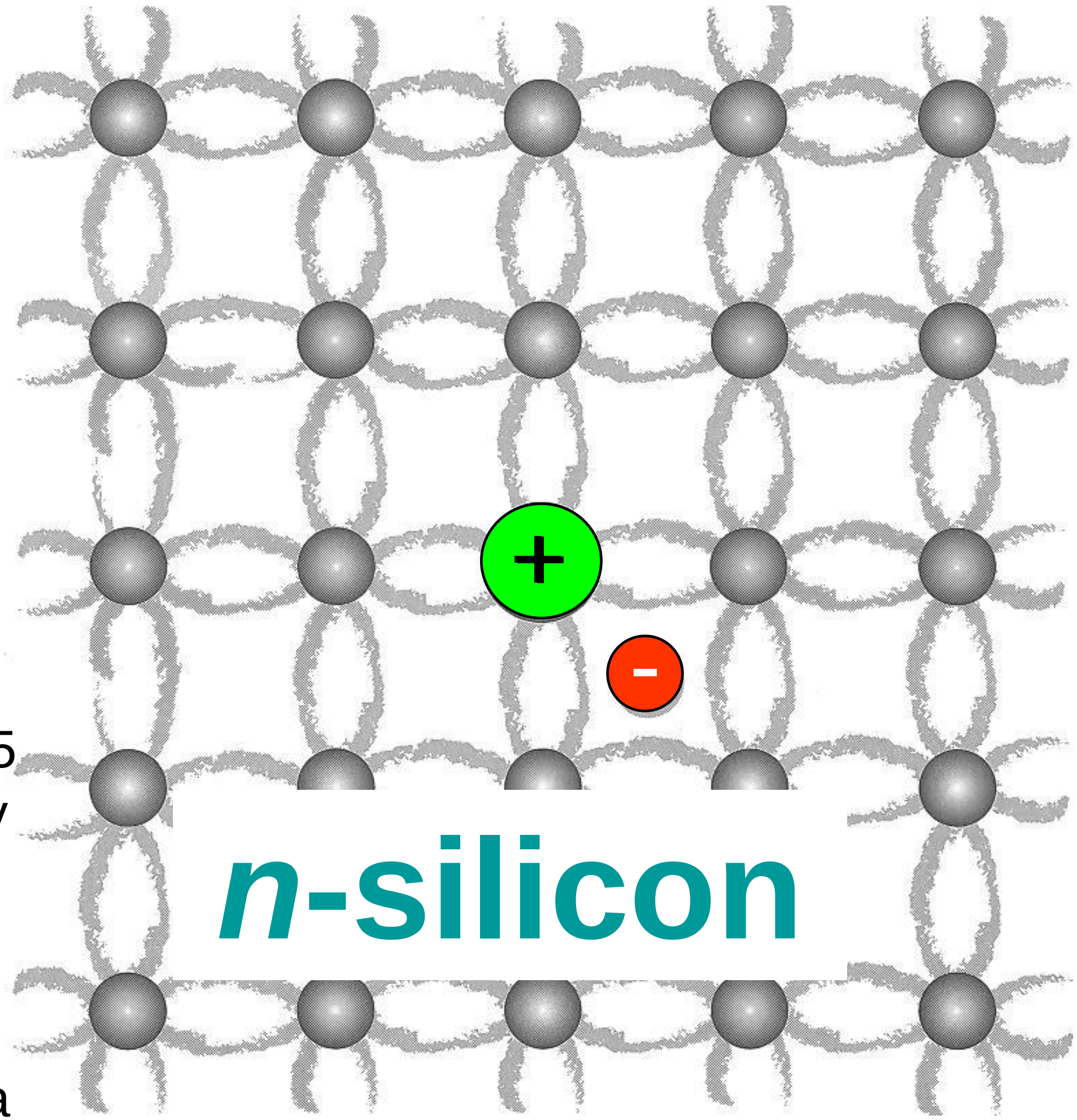
Silicon doped with **Phosphorus** atoms.

Phosphorus has 5 electrons in the valence band (one more than Silicon).

There is an extra electron that tends to become free: acts as a **carrier**.

The **Phosphorus** kernel has +5 charge, and cristal site has only 4 covalent bond electrons.

Thus the site has +1 positive charge. Since it is attached to the lattice, is not a carrier: it is a **donor**.



Extrinsic (doped) semiconductor: number of free electrons > number of holes

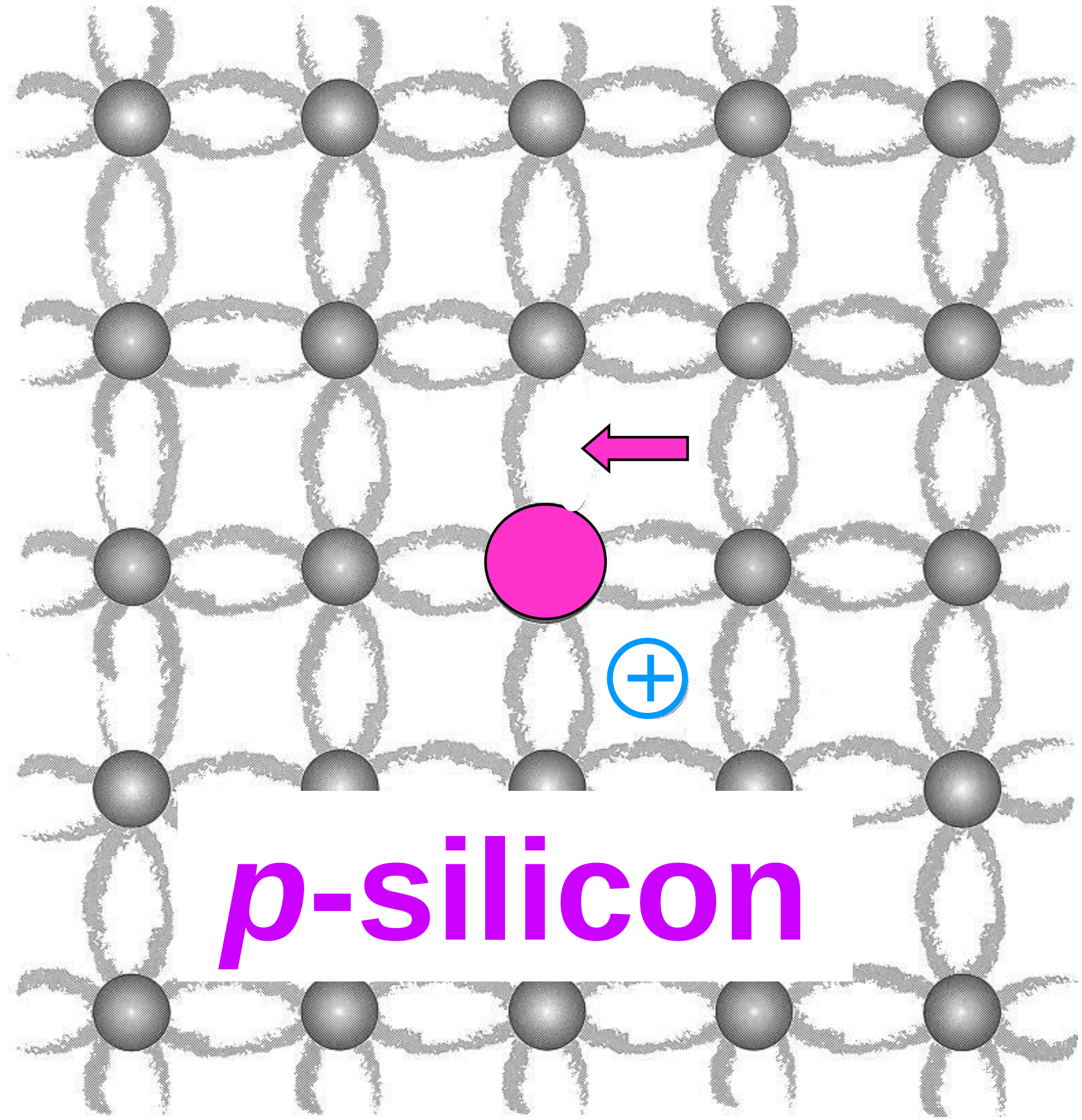
Silicon doped with **Boron** atoms.

Boron has 3 electrons in the valence band (one less than Silicon).

Only 3 covalent bonds are satisfied, leaving one incomplete, i.e. leaving a **free hole**.

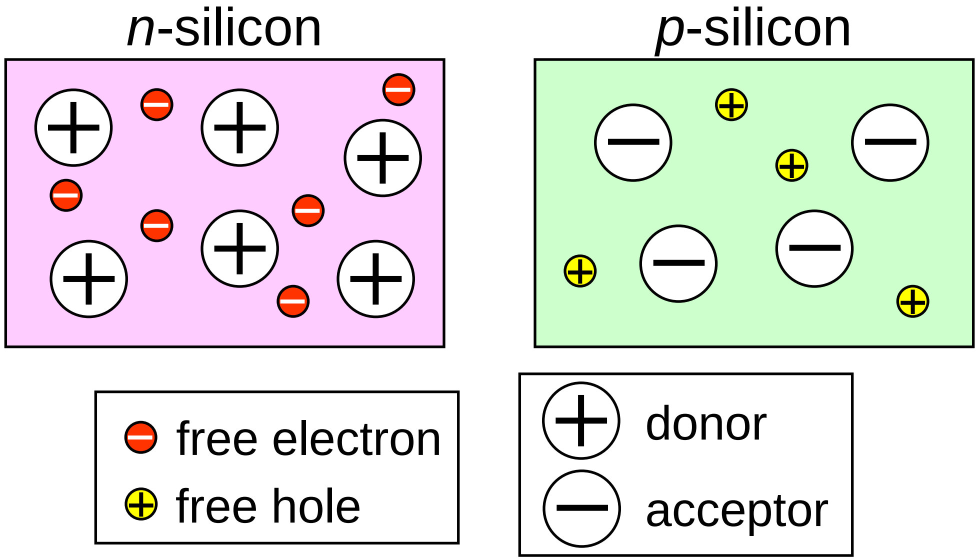
The dominant carrier is **free-hole**.

The **Boron** atom represents a -1 immobile charge: it is an **acceptor**.



Extrinsic (doped) semiconductor: number of free electrons < number of holes

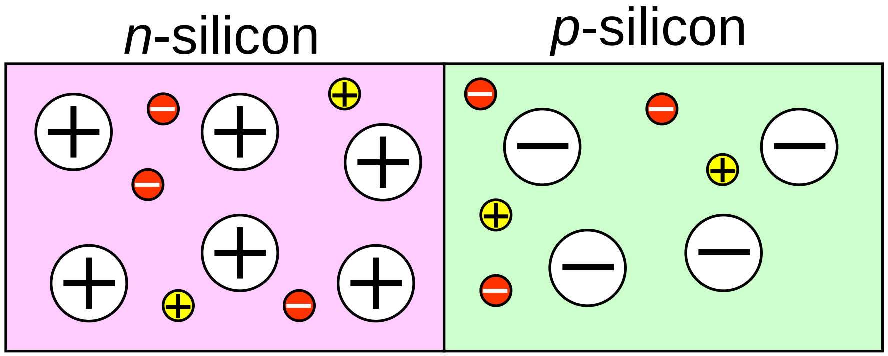
Before joining, both *n*-material and *p*-material are electrically neutral.



Electrons, more abundant in *n*-side, tend to diffuse to *p*-side.

Holes tem to diffuse from *p*-side to *n*-side.

Donors and acceptors cannot move.



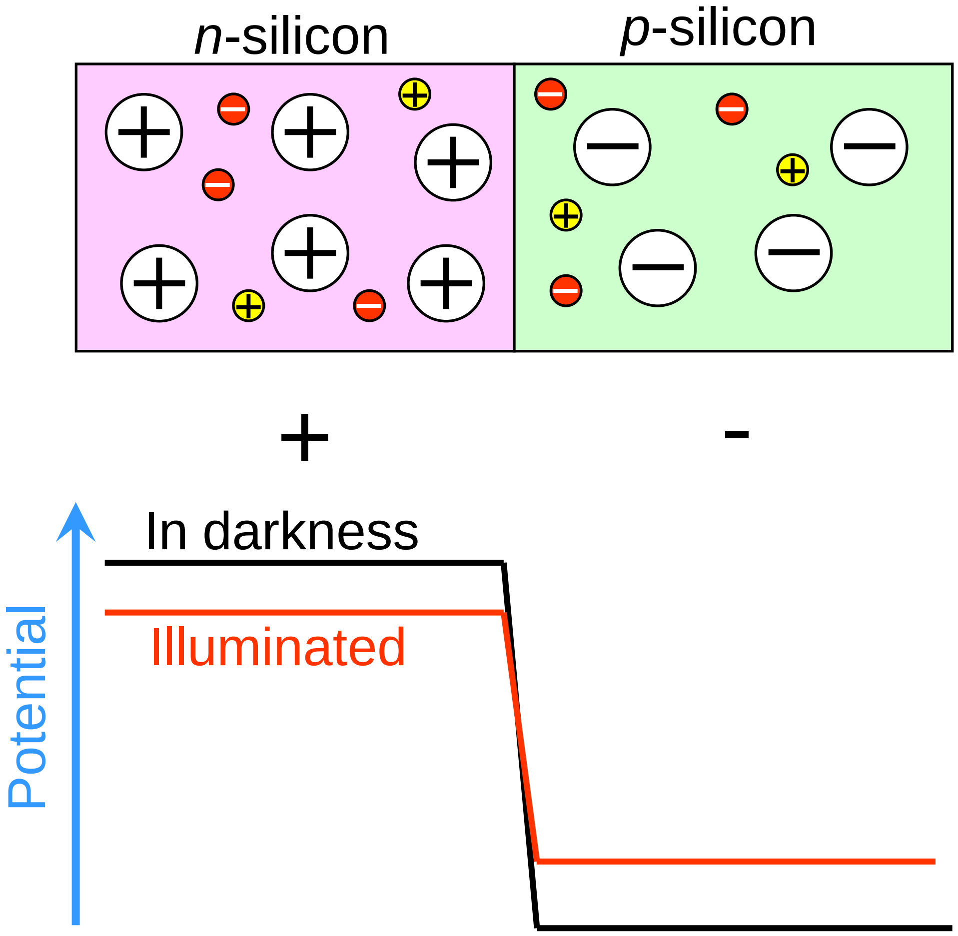
The *n*-side becomes positive and the *p*-side becomes negative.

A contact potential is created. In silicon, at room temperature, it can be around 1 V, depending on the doping.

The potential accross most of the *n*-side and *p*-side is constant (no electric field).

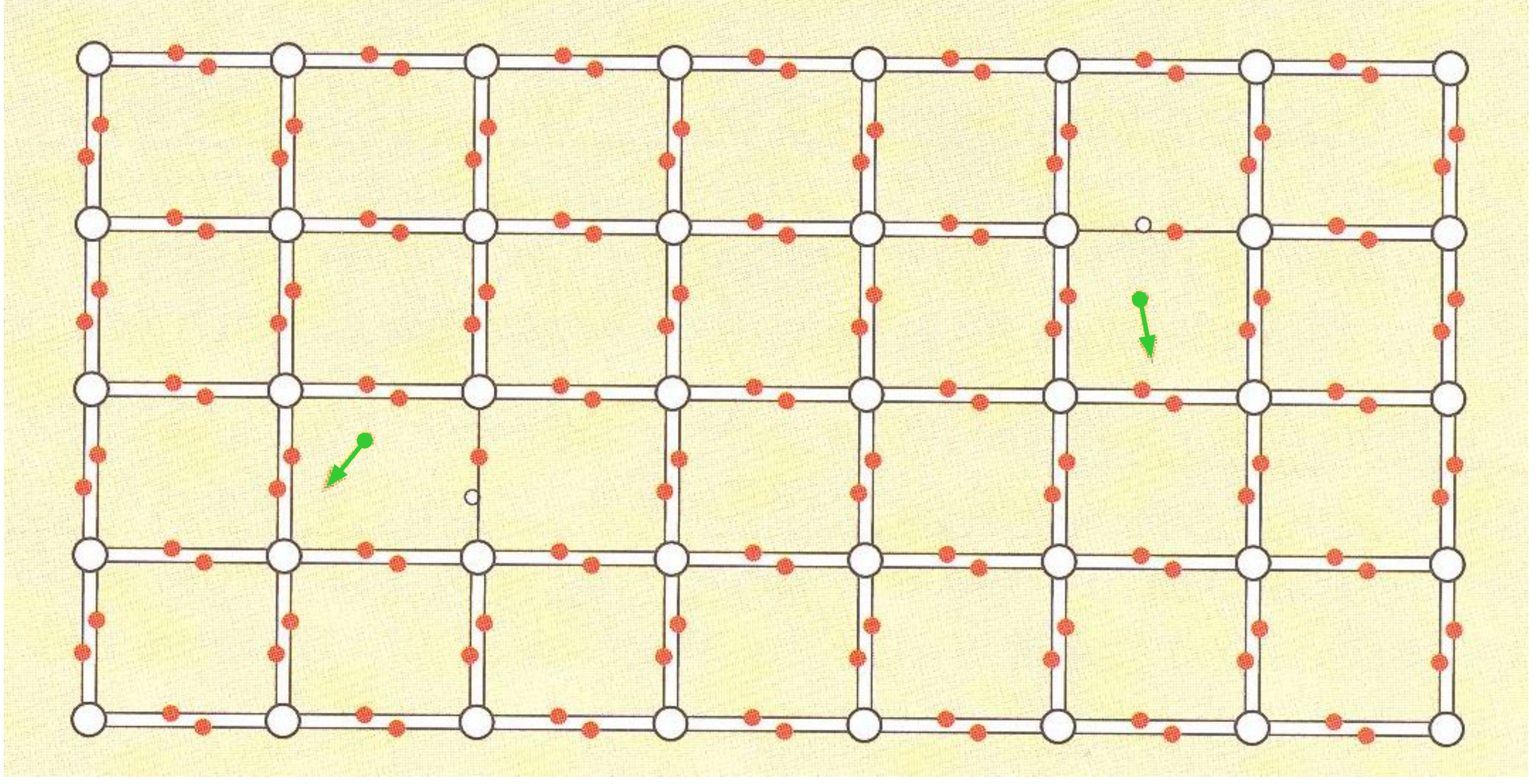
All the field is concentrated across a narrow transition region.

Owing to the narrowness of this region (a few tens of a nano-meter), the electric field can be enormous (tens of millions of volts/meter).



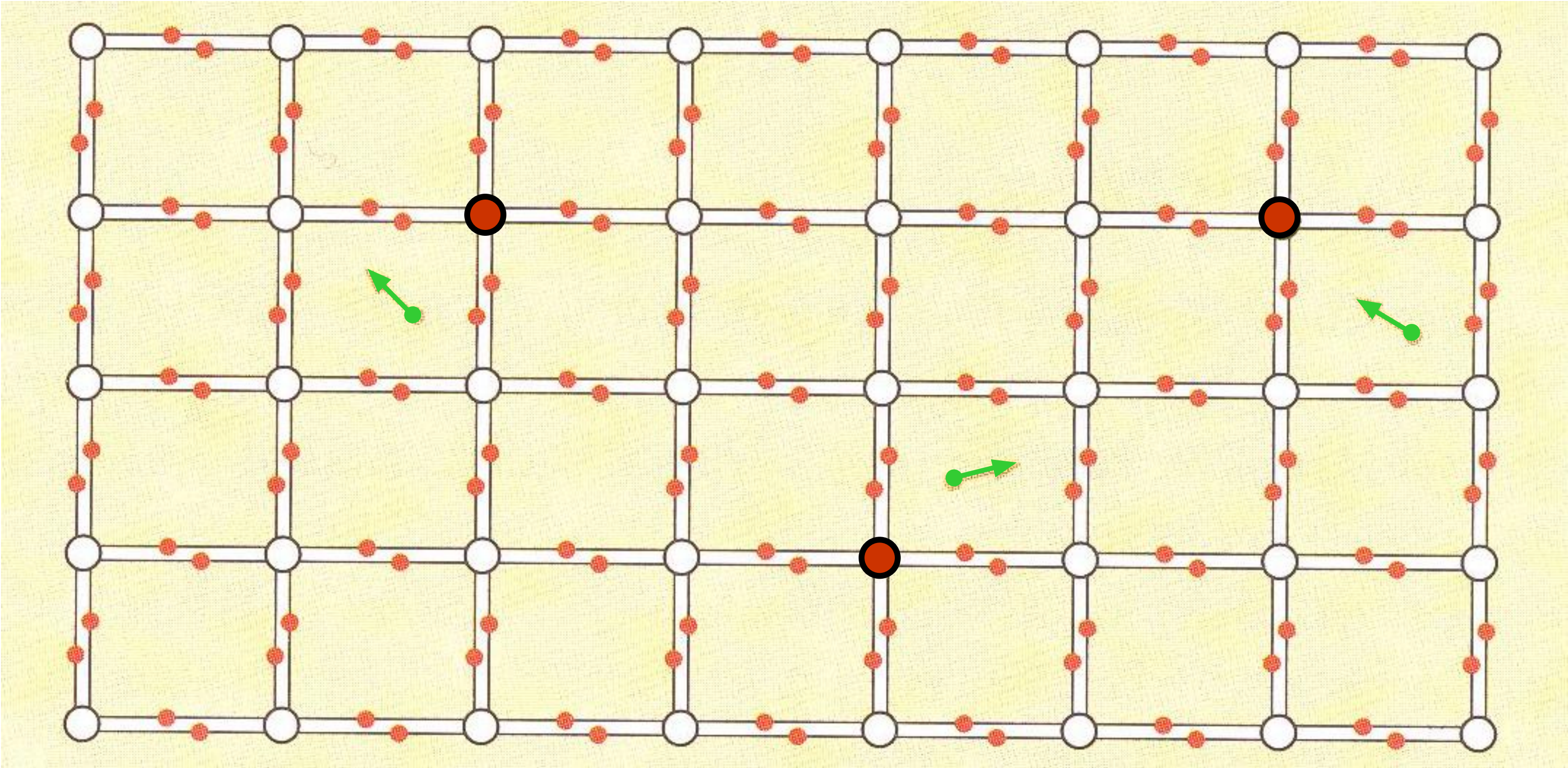
When light shines near a *p*-*n* junction, electron-hole pairs may be created on either side. If they are very far from the transition zone, they will recombine after a few microseconds. If, however, they are near, they may drift toward the region of high electric field. In this case, an electron created on the *p*-side may fall to the *n*-side, while the hole created on the *n*-side may fall to the *p*-side. In either case, these charges counteract the contact potential. Thus the effect of light on a *p*-*n* junction is the lowering of the contact potential.

Pure Silicon



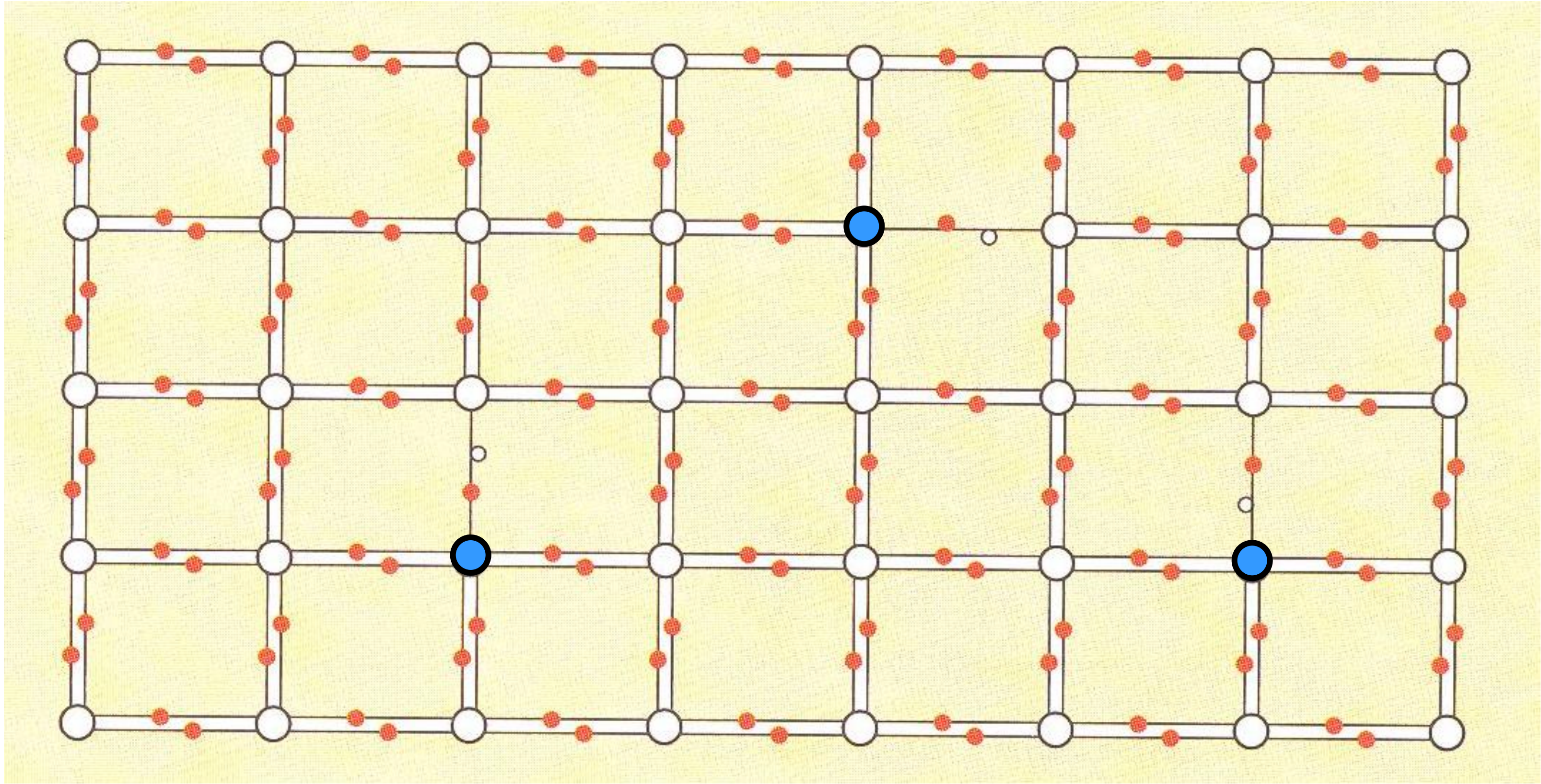
Number of **free electrons** = number of **holes**

n-Silicon



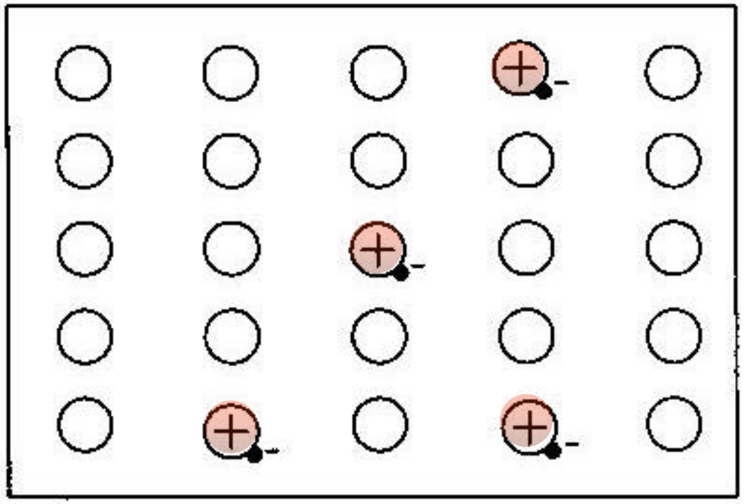
Number of **free electrons** > number of **holes**

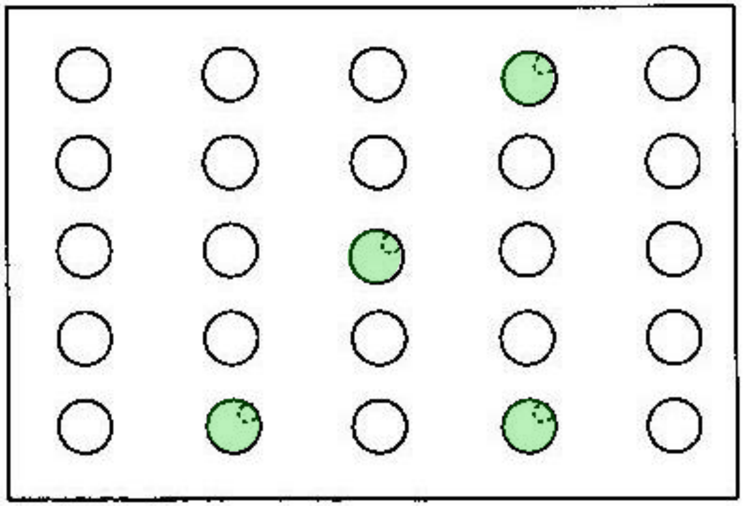
p-Silicon



Number of **free electrons** < number of **holes**

Doped semiconductors





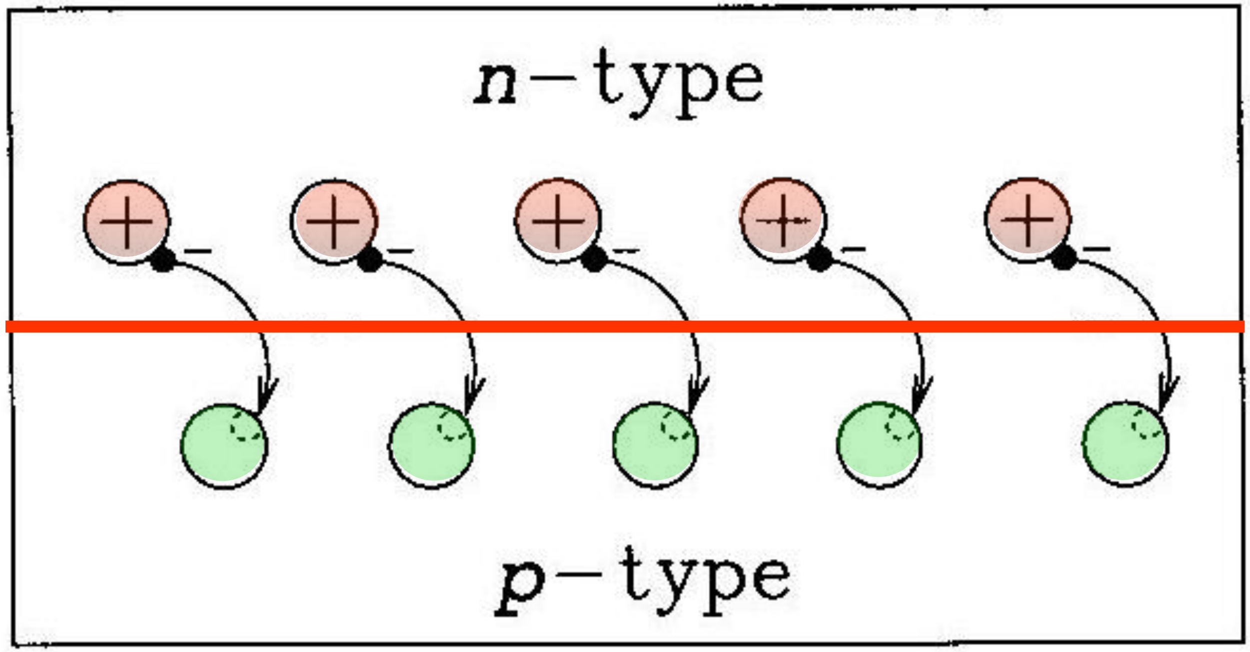
n-type, with “excess” electrons ●⁻

p-type, with “excess” positive holes ◌

Typically the amount of doping is very small:

- Extremely heavy doping: 1 doping atom per 10 000 silicon atoms.
- Very light doping: 1 doping atom per 10^8 silicon atoms.

At a $p-n$ junction

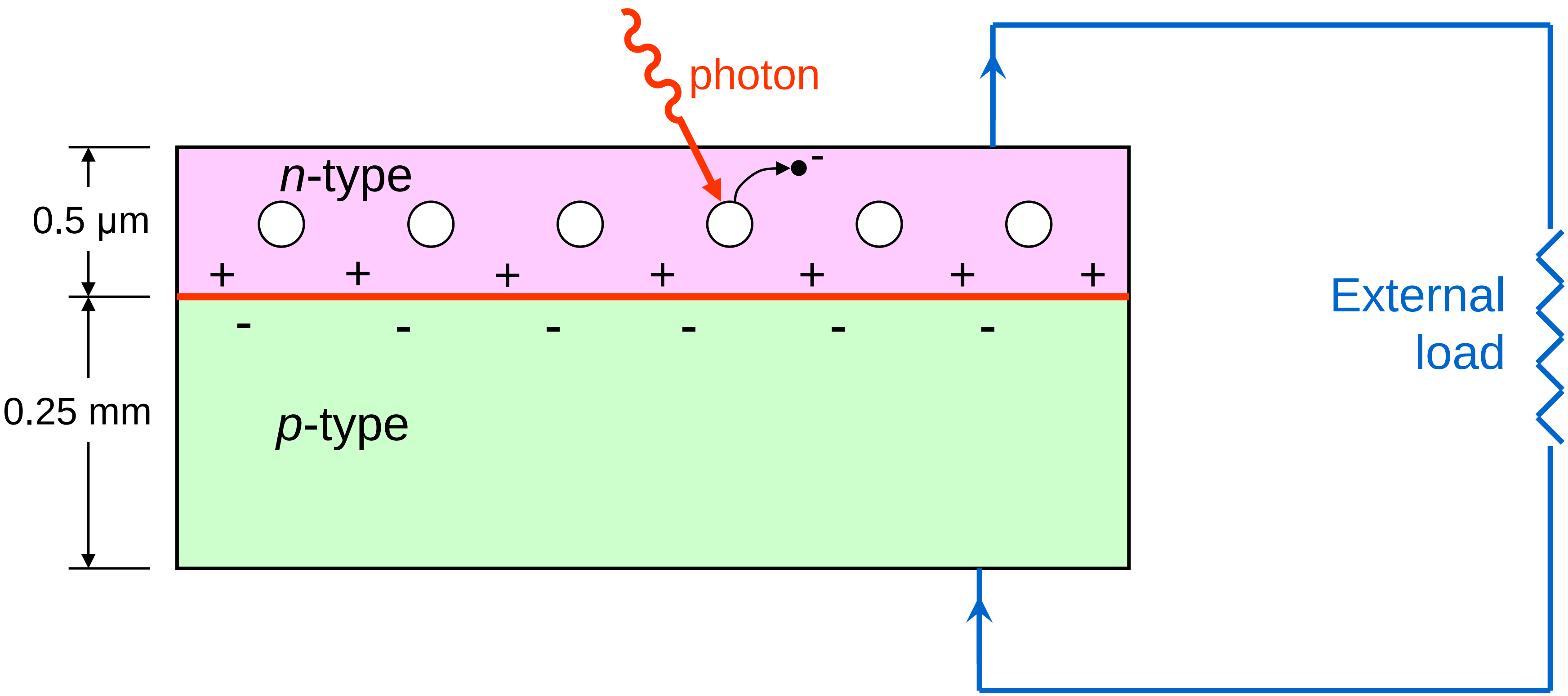


Excess electrons ● from *n*-material jump to fill "excess" holes on the *p*-side of a ***p-n* junction**, leaving the *n*-side positively charged and the *p*-side negatively charged.

This restricts the the movement of additional electrons from the *n*-side to the *p*-side, while the movement of additional electrons from the *p*-side to the *n*-side is made easier.

This restriction makes the *p-n* junction to beave like a diode.

Schematic representation of a photovoltaic device



Analysis of a photovoltaic cell

I = current intensity (A)

$J = I/A$ = current density (per unit area of cell) (A/m^2)

V = voltage (V)

P = power (W)

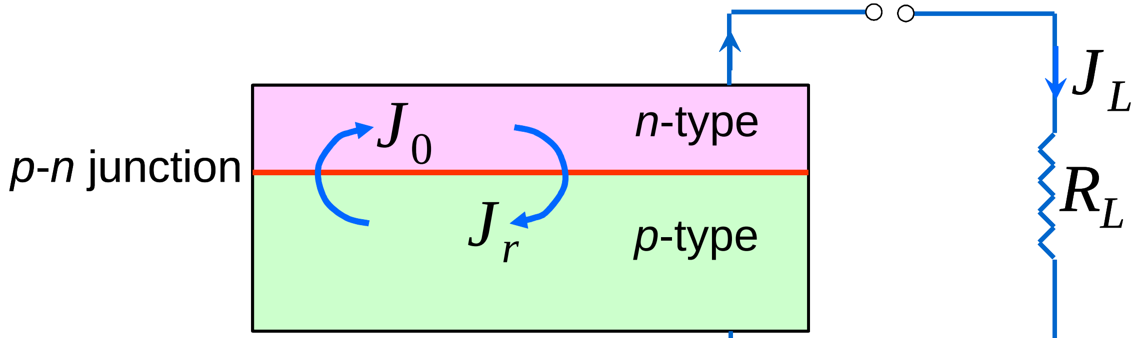
T = absolute temperature (K)

e_0 = charge of an electron = 1.602 10^{-19} J/V

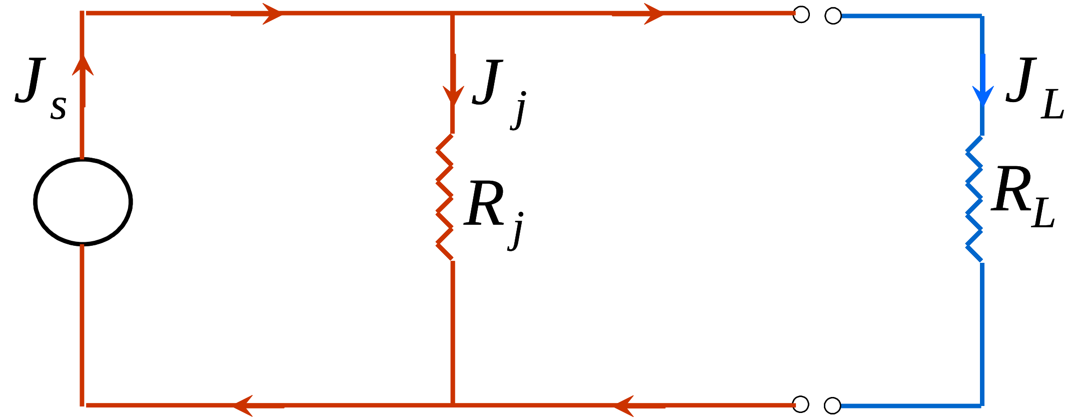
k = Bolzmann constant = 1.381 10^{-23} J/K

J_0= **dark current** or **reverse saturation current**

J_r = **light-induced recombination current**



Depending on temperature ***T***, some electrons on *p*-side exist in conduction band, and can easily move to *n*-side to fill holes created at *p*-*n* junction. This produces the **dark current** J_0**.**



Depending on temperature ***T***, some electrons on *n*-side exist in the conduction band. Normally they do not have enough energy to cross the *p*-*n* junction.

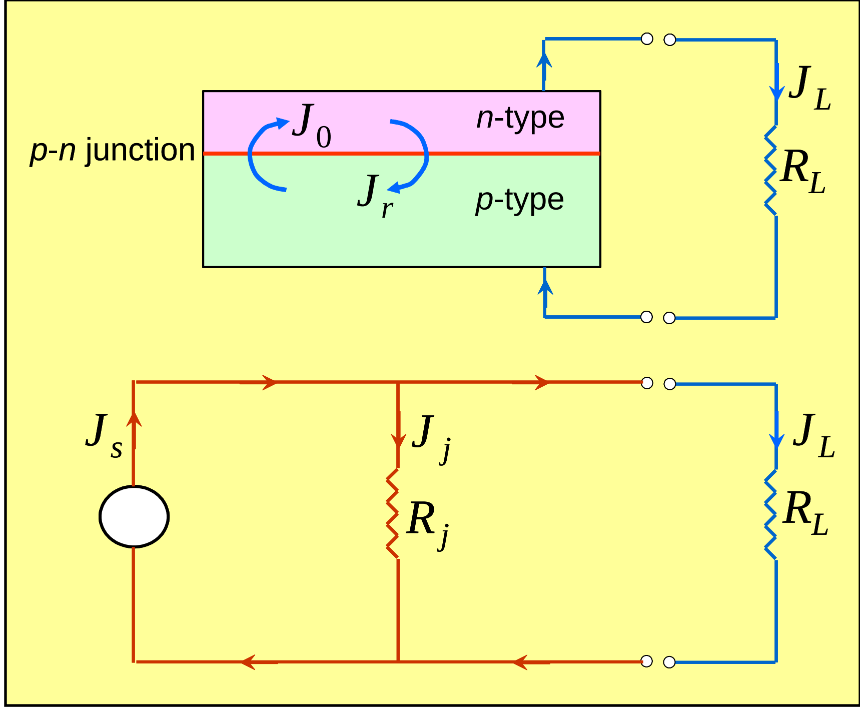
However, if a forward bias voltage ***V*** is applied, due to the action of the photons of light, some electrons have enough energy to cross and recombine with the hole in the *p*-side. This gives rise to the **light-induced recombination current** J_r **.**

J_r is proportional to J_0

$$J_r = J_0 \exp(e_0 V / kT)$$

$$J_r = J_0 \exp(e_0 V / kT)$$

$$J_j = J_r - J_0 = J_0\left[\exp(e_0 V / kT) - 1\right]$$



External current:

$$J_L = J_s - J_j$$

$$= J_s - J_0\left[\exp(e_0 V / kT) - 1\right]$$

J_s = **short-circuit current**

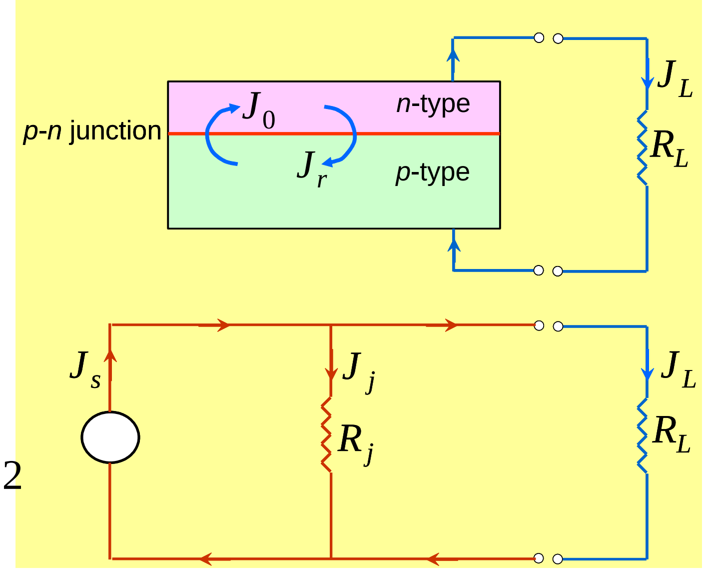
Short circuit: $R_L = 0, \quad V = 0 \quad \Rightarrow \quad J_L = J_s$

Open circuit: $J_L = 0 \quad \Rightarrow \quad V = V_{oc}$

$$0 = J_s - J_0\left[\exp\left(e_0 V_{oc} / kT\right) - 1\right] \quad \Rightarrow \quad \boxed{V_{oc} = \frac{kT}{e_0} \ln\left(\frac{J_s}{J_0} + 1\right)}$$

open-circuit voltage

Exercise



Consider a silicon cell exposed to solar radiation of 900 W/m^2.

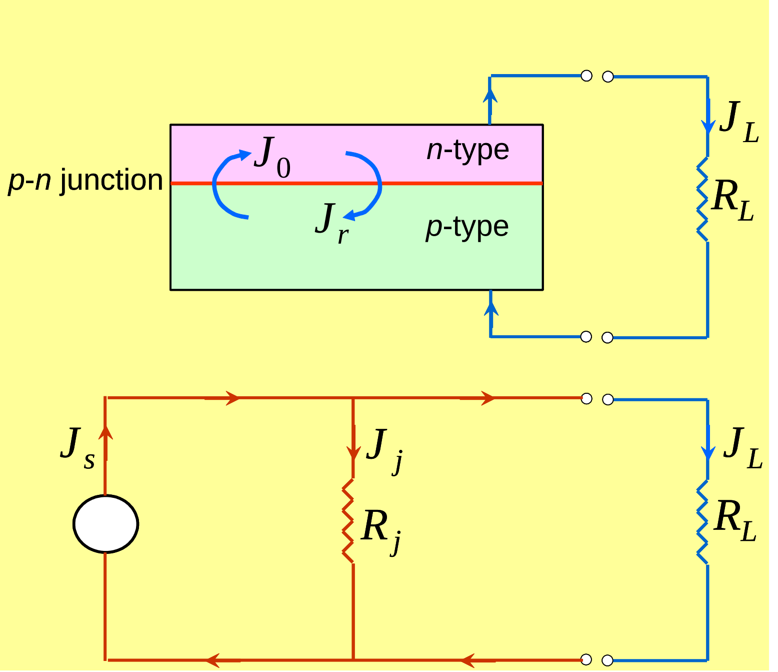
- Temperature $T = 40°\mathrm{C} = 313\mathrm{K}$
- Dark current density $J_0 = 1.8\times10^{-8}\,\mathrm{A/m^2}$
- Short-circuit current density $J_s = 200\,\mathrm{A/m^2}$

Plot the external current density J_L versus voltage V.

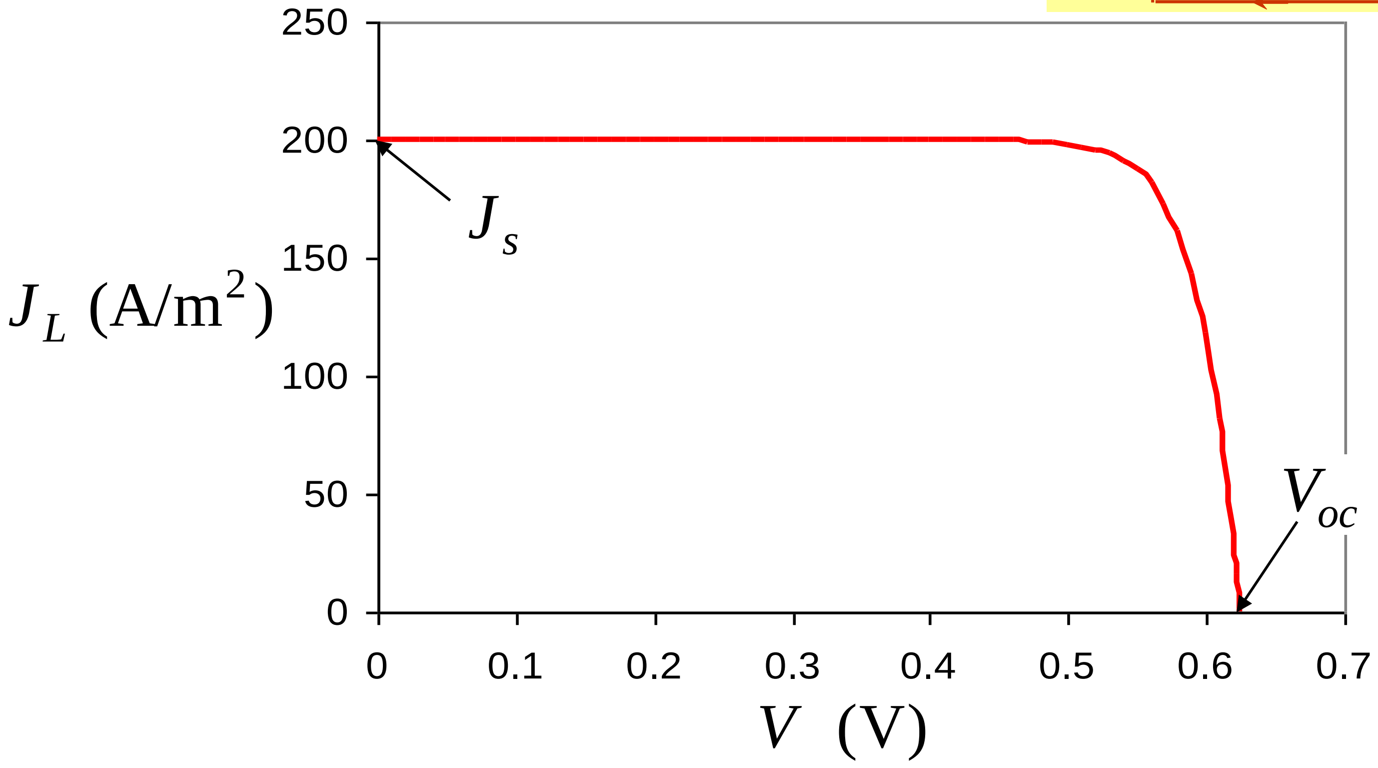
$$\frac{e_0}{kT} = \frac{1.602\times10^{-19}}{1.381\times10^{-23}\times313} = 37.06\,\mathrm{V}^{-1}$$

$$V_{oc} = \frac{kT}{e_0}\ln\left(\frac{J_s}{J_0}+1\right) = \frac{1}{37.06}\ln\left(\frac{200}{1.8\times10^{-8}}+1\right) = 0.624\,\mathrm{V}$$

$$J_L = J_s - J_0\left[\exp\frac{e_0 V}{kT} - 1\right] = 200 - 1.8\times10^{-8}\left[\exp(37.06V) - 1\right]$$



$$J_L = 200 - 1.8\times10^{-8}[\exp(37.06V) - 1]$$



Electrical power

Power output = load current × voltage

$P = I_L V = AJ_L V = I_L^2 R_L$ (A = area of cell, R_L =load resistance)

$$\boxed{P = AV\left[J_s - J_0\left(\exp\frac{e_0 V}{kT} - 1\right)\right]}$$

Condition for maximum $P = P_{\max}$ when $V = V_m$ such that $\frac{dP}{dV} = 0$. Gives:

$$\boxed{\left(1 + \frac{e_0 V_m}{kT}\right)\exp\frac{e_0 V_m}{kT} = 1 + \frac{J_s}{J_0}}$$

$$\boxed{J_{L,m} = J_s - J_0\left[\exp\frac{e_0 V_m}{kT} - 1\right] = \frac{\frac{e_0 V_m}{kT}}{1 + \frac{e_0 V_m}{kT}}(J_s + J_0)}$$

$$\boxed{P_{\max} = AV_m\left[J_s - J_0\left(\exp\frac{e_0 V_m}{kT} - 1\right)\right] = \frac{\frac{e_0 V_m^2}{kT}}{1 + \frac{e_0 V_m}{kT}}(J_s + J_0)\,A}$$

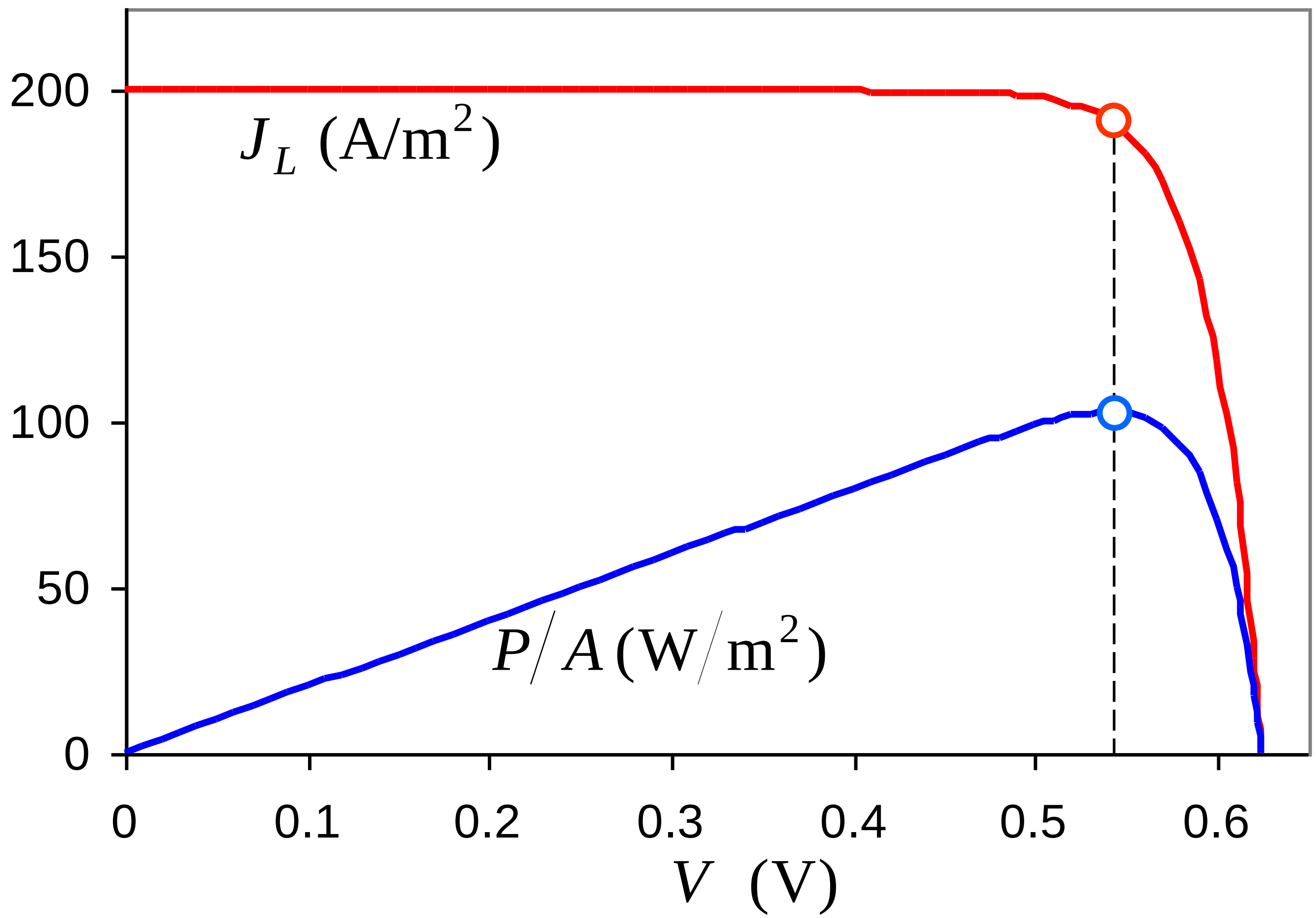
Exercise (continuation)

- Plot power output (per unit area) P/A versus V.
- Determine $V_m,\ J_{L,m},\ P_{\max}/A$.

$$\left(1+\frac{e_0 V_m}{kT}\right)\exp\frac{e_0 V_m}{kT}=1+\frac{J_s}{J_0} \quad\Longrightarrow\quad V_m = 0.542\ \mathrm{V}$$

$$J_{L,m}=\frac{\dfrac{e_0 V_m}{kT}}{1+\dfrac{e_0 V_m}{kT}}\left(J_s+J_0\right) \quad\Longrightarrow\quad J_{L,m}=190.5\ \mathrm{A/m^2}$$

$$\frac{P_{\max}}{A}=\frac{\dfrac{e_0 V_m^2}{kT}}{1+\dfrac{e_0 V_m}{kT}}\left(J_s+J_0\right) \quad\Longrightarrow\quad P_{\max}/A=103.2\ \mathrm{W/m^2}$$



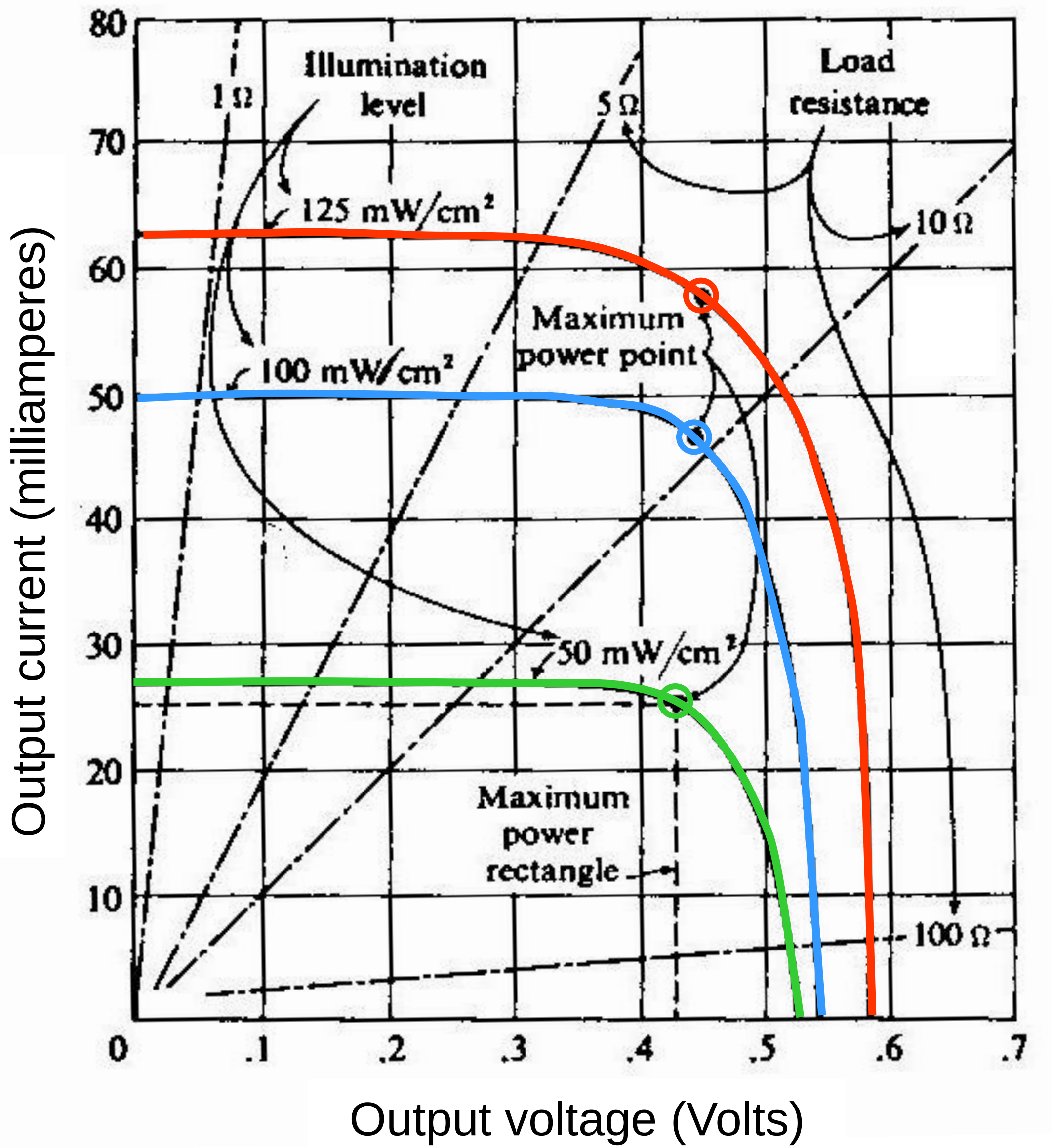
200
150
100
50
0
J_L (A/m^2)
P/A (W/m^2)
0
0.1
0.2
0.3
0.4
0.5
0.6
V (V)

Exercise (continuation)

- Determine maximum efficiency (remember that solar radiation is 900 W/m^2).
- Determine the cell area *A* required for an output of 25 W (at maximum efficiency conditions).

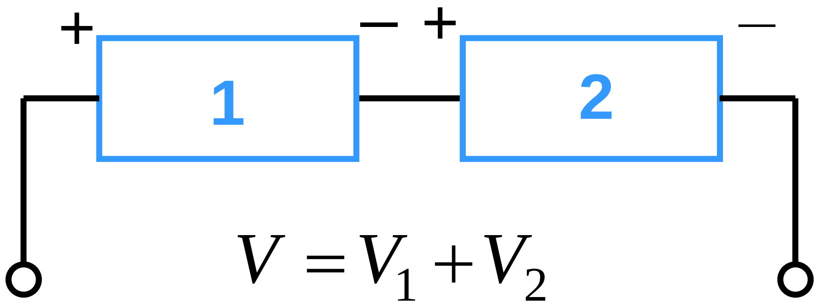
$$\eta_{\max} = \frac{P_{\max}/A}{900} = \frac{103.2}{900} = 0.115 = 11.5\%$$

$$A = \frac{P_{\text{out}}}{P_{\max}/A} = \frac{25}{103.2} = 0.242\ \text{m}^2 = 24.2\ \text{cm}^2$$



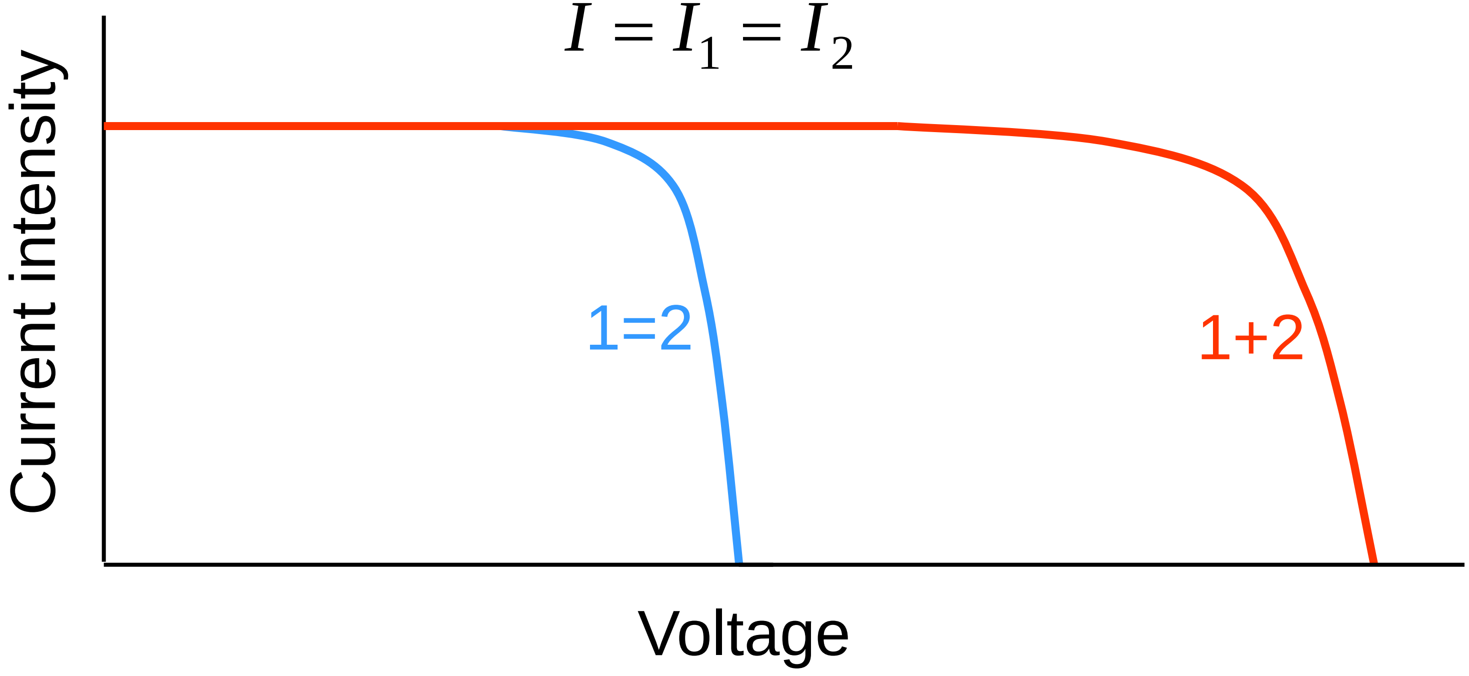
Typical current-voltage characteristics of a silicon cell, showing effects of **illumination level** and **load resistance**.

Characteristics of two similar cells connected in series

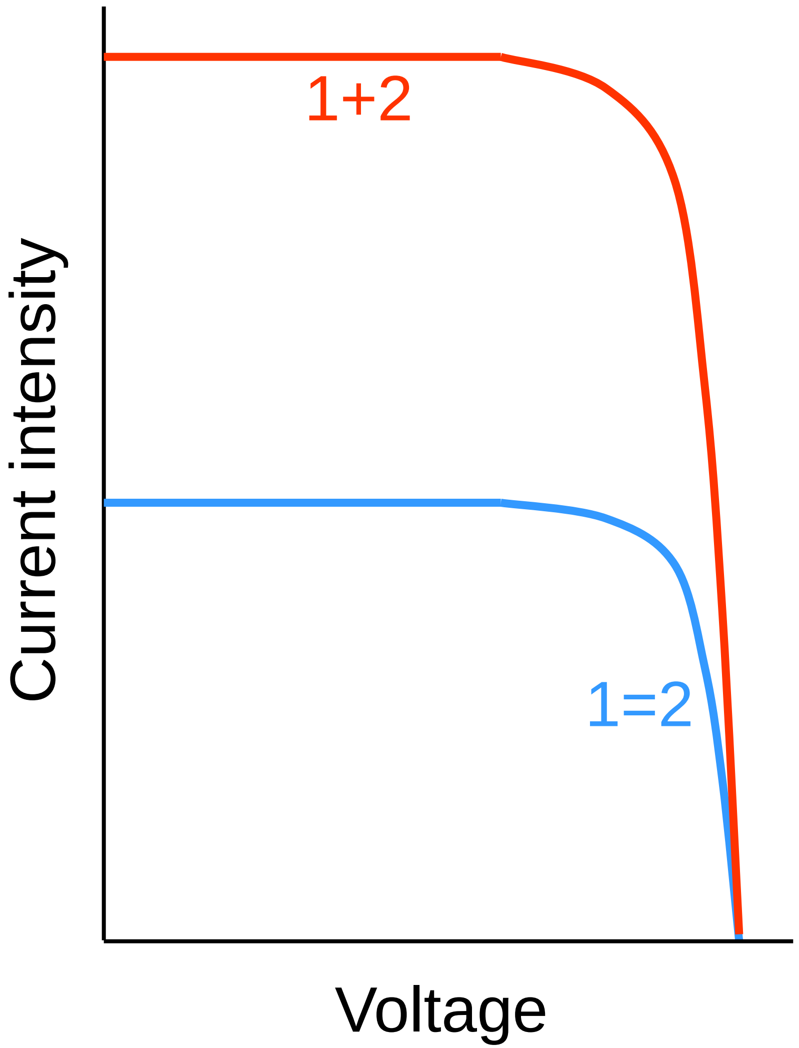


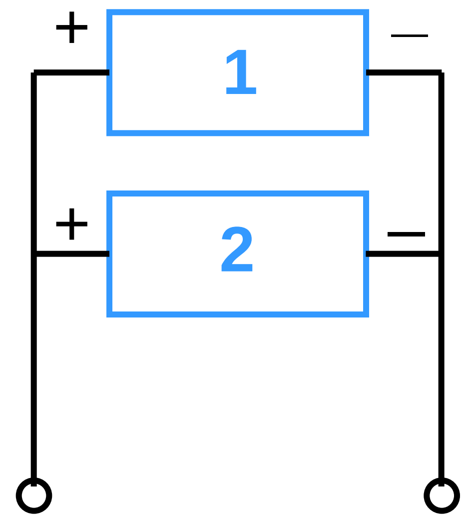
$$V = V_1 + V_2$$

$$I = I_1 = I_2$$



Characteristics of two similar cells connected in parallel

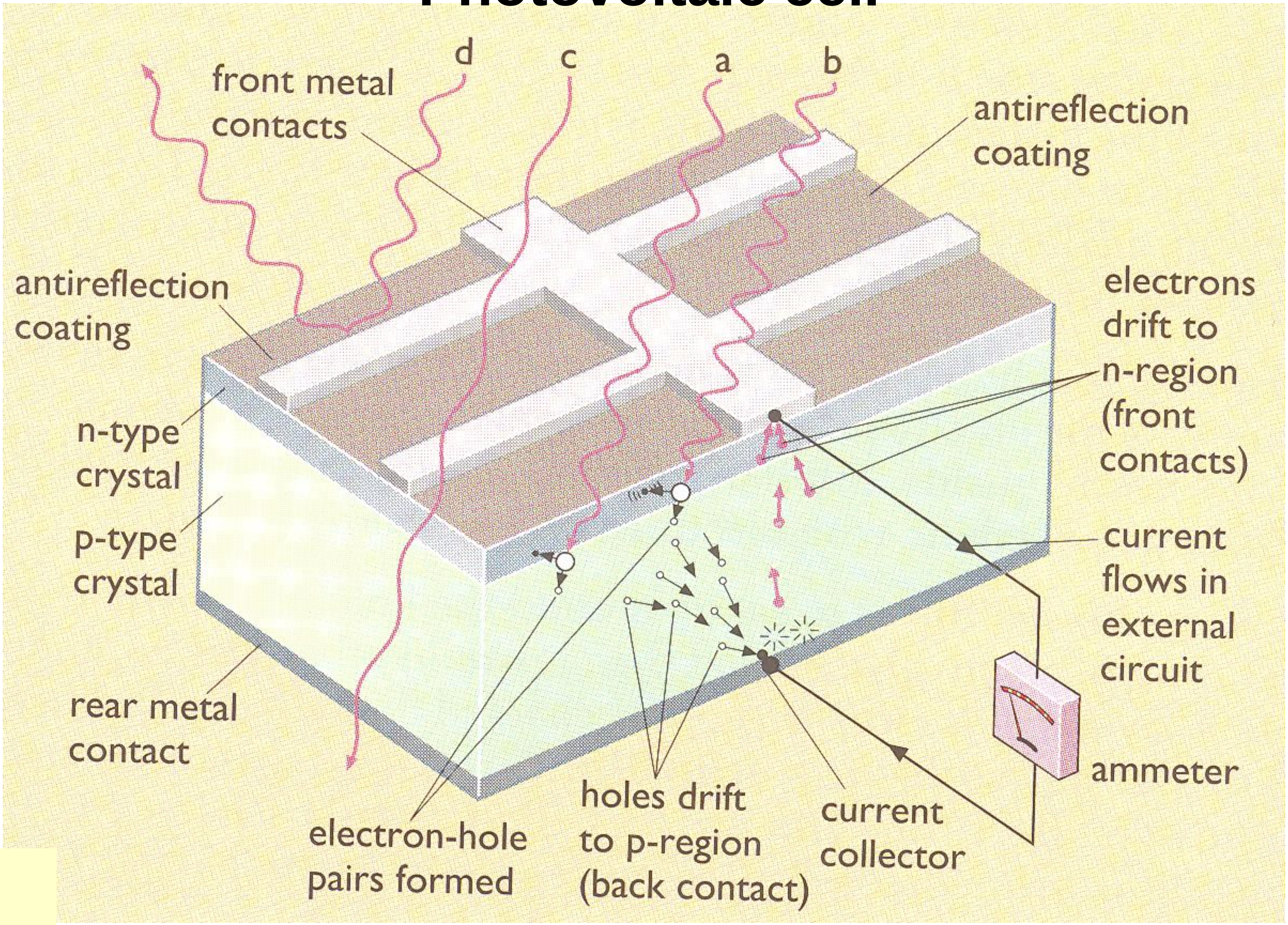




$$V = V_1 = V_2$$

$$I = I_1 + I_2$$

Photovoltaic cell



Efficiency of PV solar cells

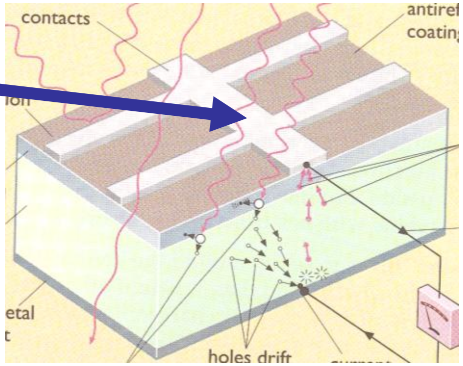
There are several reasons for the **actual efficiency** of solar cells being lower than the **theoretical efficiency**:

Reflection of light from the cell surface.

This can be reduced (from ~30% to ~3%) by anti-reflection coating)

Shading of the cell due to current collecting electrical contacts.

This can be minimized by reducing area of contacts, but this will increase the electrical resistance of cell.



Internal resistance of the cell.

Recombination of electrons and holes before they can contribute to the current.

Can be minimized by using hydrogen alloys.

Multijunction solar cells

This is a way of achieving **higher total conversion efficiency** by **capturing a larger portion of the solar spectrum**.

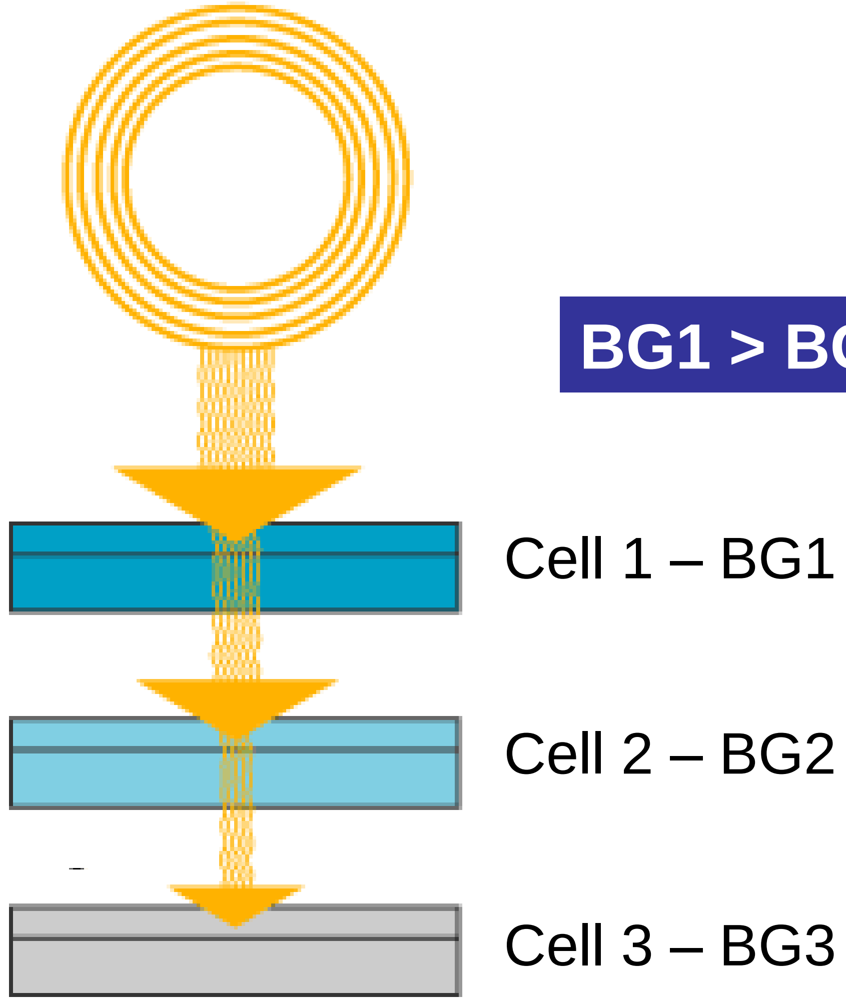
Individual cells with different bandgaps are stacked on top of one another, in such a way that **sunlight falls first on the material having the largest bandgap**.

Photons not absorbed in the first cell are transmitted to the second cell, which then absorbs the higher-energy portion of the remaining solar radiation while remaining transparent to the lower-energy photons.

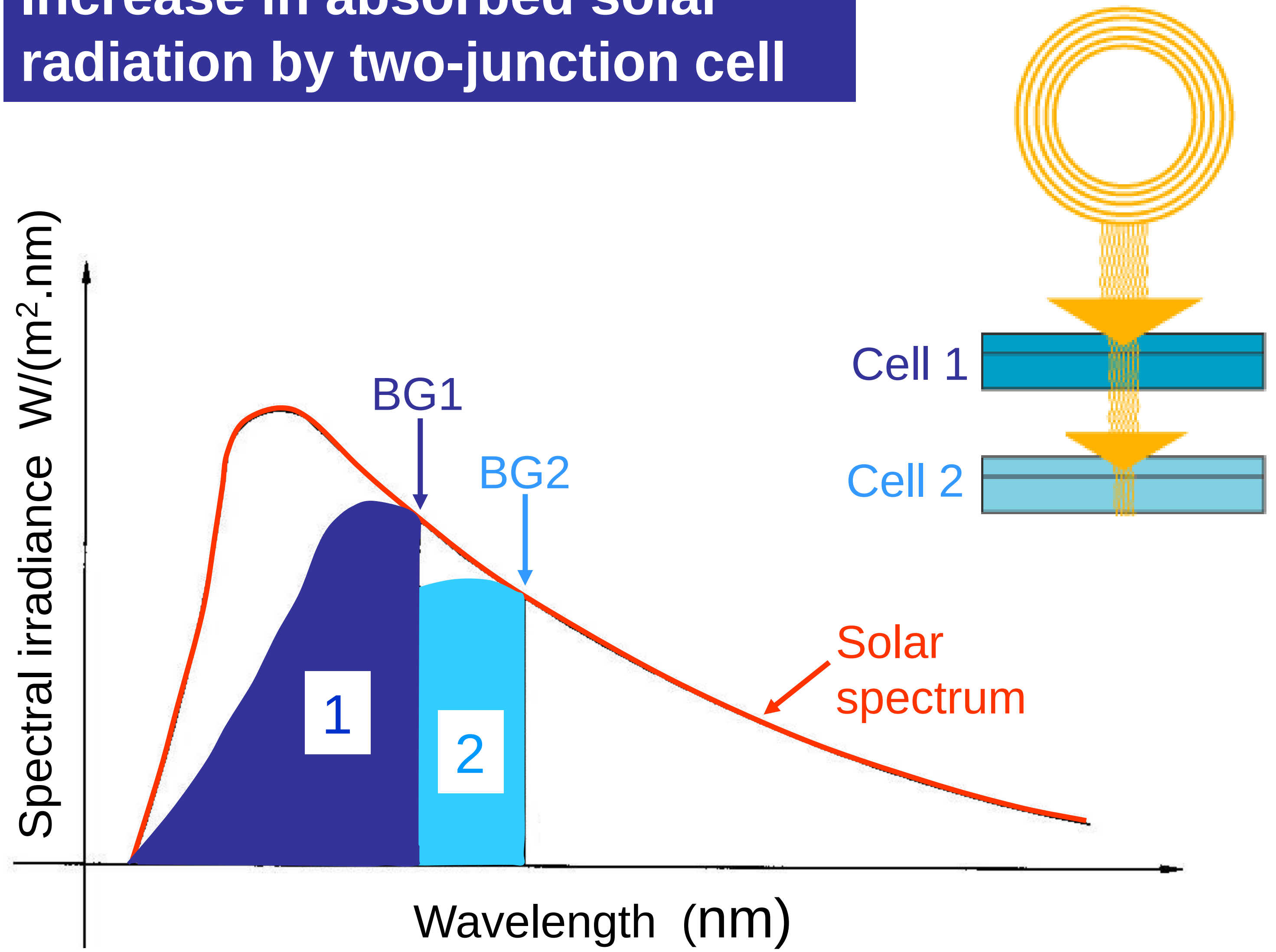
These selective absorption processes continue through to the final cell, which has the smallest bandgap.

Multijunction solar cells

BG1 > BG2 > BG3



Increase in absorbed solar radiation by two-junction cell



Exercise

A PV application requires a power of 300 W at a voltage of 28 V.

Design a PV panel using cells from the previous exercise, each with an area of 6 cm^2.

$$V_m = 0.542\ \text{V} \qquad I_m = 190.5 \times A = 190.5 \times 6 \times 10^{-4} = 0.1143\ \text{A}$$

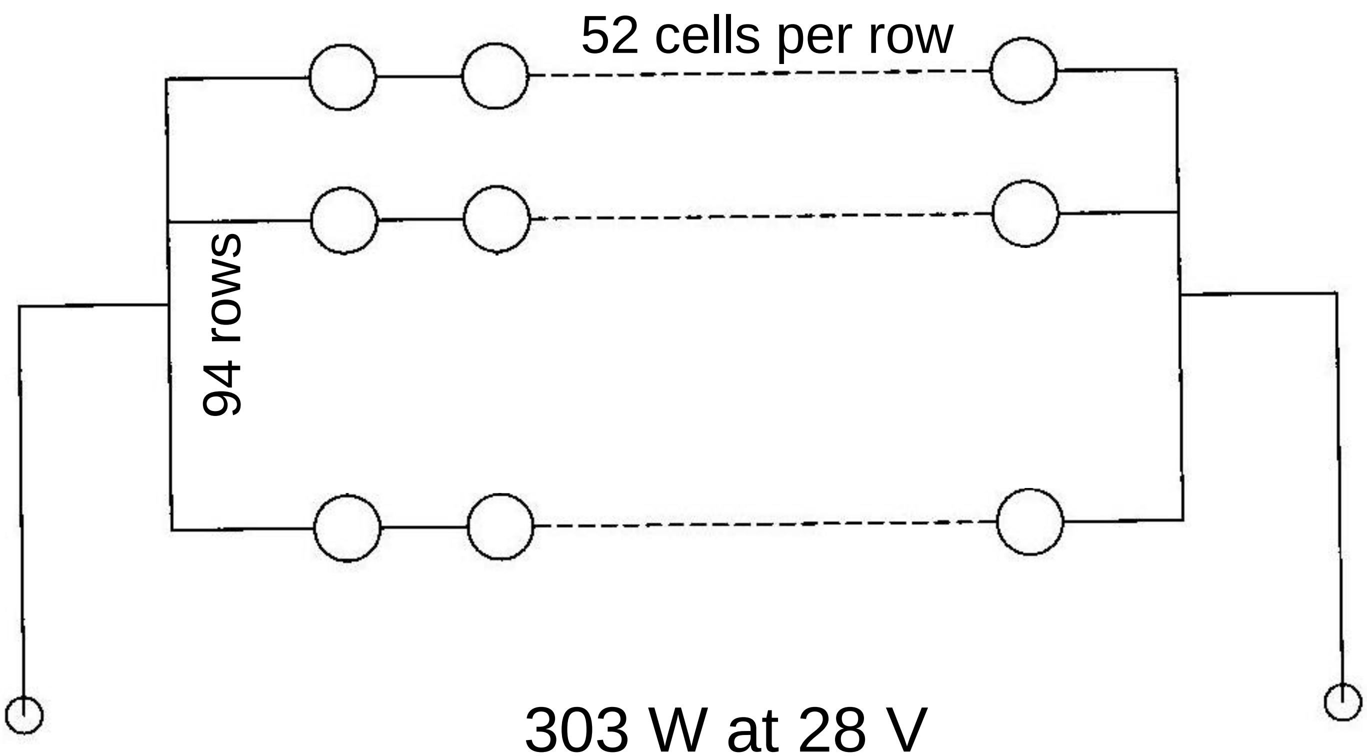
$$\text{Power/cell} = 0.542 \times 0.1143 = 0.0620\ \text{W}$$

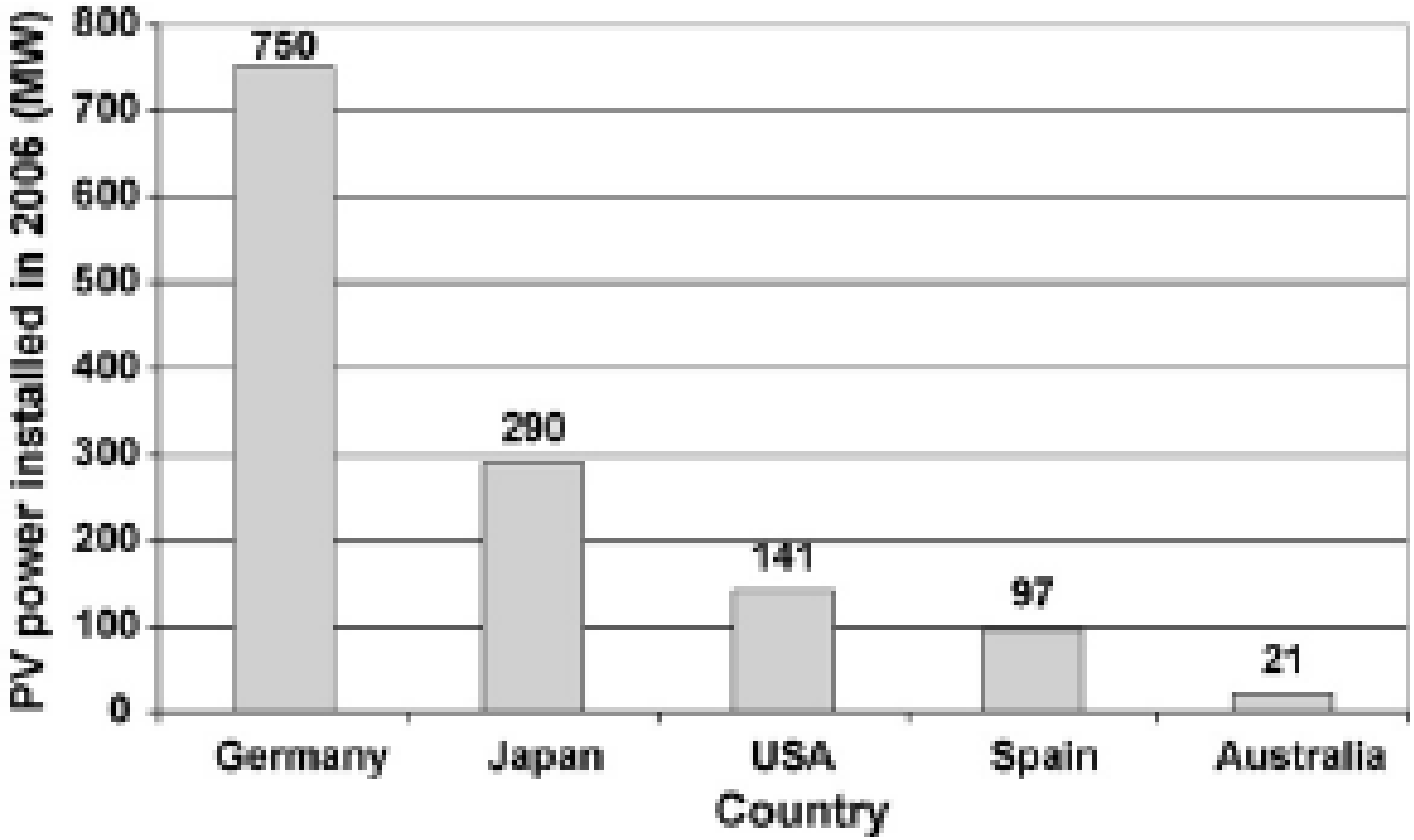
$$\text{Number of cells required} = \frac{300}{0.0620} = 4840$$

$$\text{Number of cells in series} = \frac{\text{system voltage}}{\text{voltage per cell}} = \frac{28}{0.542} = 51.7 \cong 52$$

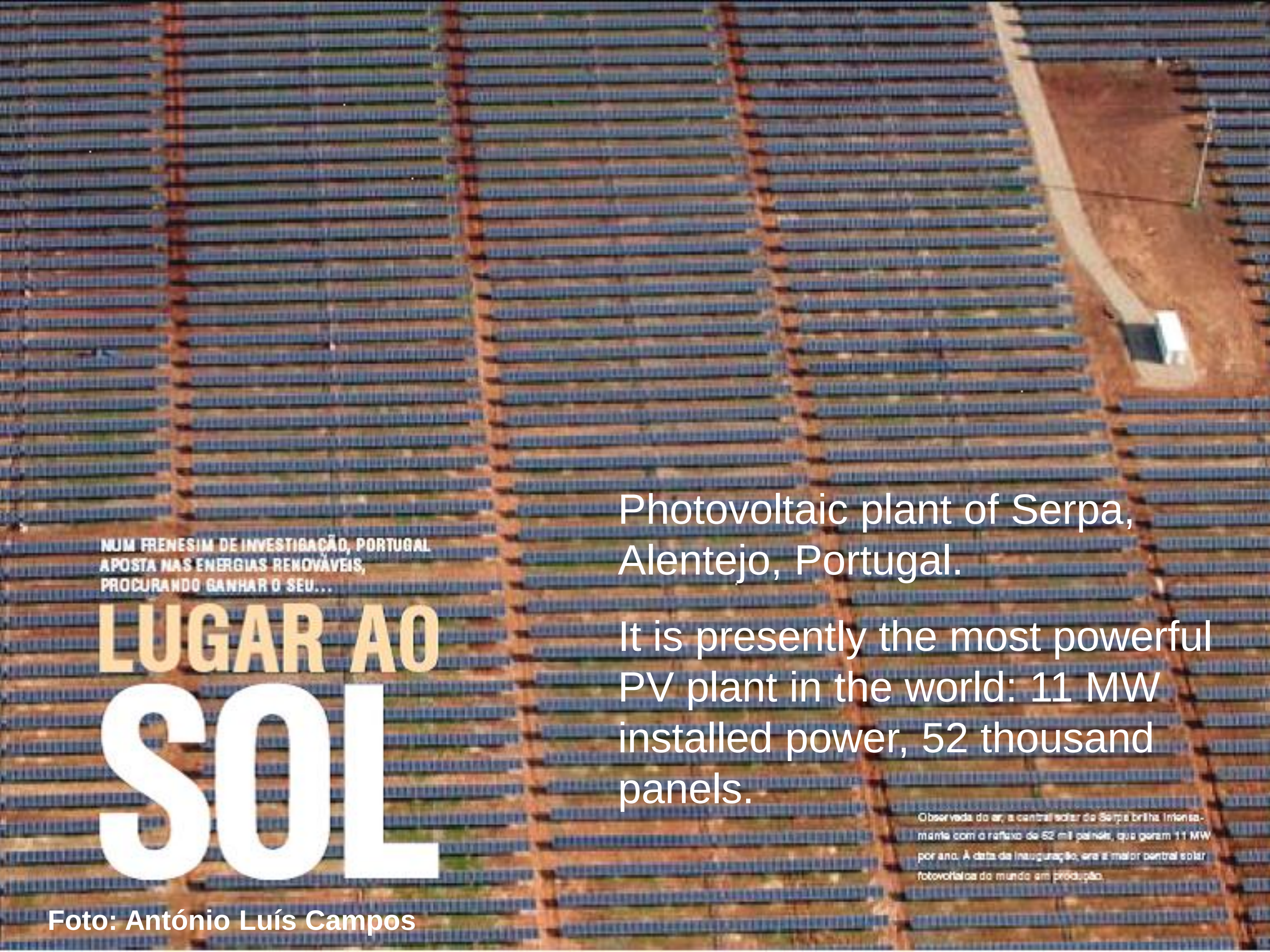
$$\text{Number of rows of 52 cells connected in parallel} = \frac{4840}{52} = 93.1 \cong 94$$

$$\boxed{\text{Total number of cells} = 52 \times 94 = 4888}$$


52 cells per row
94 rows
303 W at 28 V



PV power installed (MW) in the year of 2006 in Germany, Japan, USA, Spain and Australia.



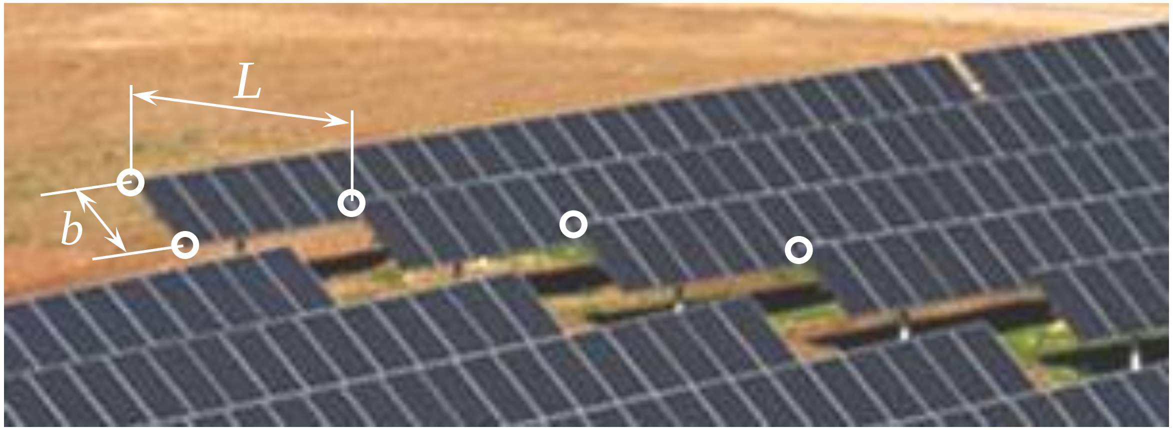
Photovoltaic plant of Serpa, Alentejo, Portugal.

It is presently the most powerful PV plant in the world: 11 MW installed power, 52 thousand panels.

Foto: António Luís Campos


Photovoltaic plant of Serpa, Alentejo, Portugal.


Photovoltaic plant of Serpa, Alentejo, Portugal.
Single-axis sun-tracking system



Exercise

Consider a large photovoltaic plant (like in Serpa, Portugal) consisting of many long rows of flat panels.

Assume that:

- The length of each panel row (in the horizontal direction) is very large; the width is b, and the pitch (horizontal distance between rows) is L.
- The rows face South (panel azimuth angle $a_w = 0$).
- Each row can rotate around a horizontal (longitudinal) axis, so that the tilt angle β can be made to vary between 0 and 90° by a **sun-tracking mechanism**.

Take into consideration that, depending on the Sun position in the sky, on the b/L ratio and on the tilt angle β, the panels can sometimes cast (partial) shade on each other.

Study the performance of the plant (assume clear days), taking into consideration:

- Maximum solar energy collection by the panels.
- The use of land area, as affected by the choice of the ratio *b*/*L*.
- A suitable control strategy for β (best exposition to sun rays while avoiding or minimizing the shade effect).

Notícia da Direcção Geral de Energia e Geologia

O grupo espanhol de construção Acciona vai investir 200 milhões de euros na maior central fotovoltaica do mundo, situada em Moura, actualmente em construção.

O investimento total será de 250 milhões de euros destina-se a construir a central solar fotovoltaica com **62 MWp** de potência instalada e uma produção anual de 88 GWh. A central, com 2520 módulos orientáveis (350 mil paineis) ficará instalada na Freguesia da Amareleja no concelho de Moura (Alentejo).

Os painéis são fabricados na China.

Photovoltaic plant at Amareleja, Moura, Portugal

Photovoltaic plant at Amareleja, Moura, Portugal

Bibliography

Most of this presentation is based on:

• D. Yogi Goswami, Frank Kreith, Jan F. Kreider, **Principles of Solar Engineering**, 2nd edition, Taylor & Francis, 2000. ISBN 1560327144.

Other books:

• Aldo V. da Rosa, **Fundamentals of Renewable Energy Processes**. Elsevier, 2005. ISBN 100120885107.

• Zekai Sen, **Solar Energy Fundamentals and Modelling Techniques**. Springer Verlag, 2008. ISBN 9781848001336.

A text in Portuguese on **Movimento e Posicionamento Relativos Terra-Sol** (with some exercises) may be downloaded from the usual site.